Safety assessment calculations: Central Assessment Case of the Normal Evolution Scenario

OPERA

OPERA-PU-NRG7331

Radioactive substances and ionizing radiation are used in medicine, industry, agriculture, research, education and electricity production. This generates radioactive waste. In the Netherlands, this waste is collected, treated and stored by COVRA (Centrale Organisatie Voor Radioactief Afval). After interim storage for a period of at least 100 years radioactive waste is intended for disposal. There is a world-wide scientific and technical consensus that geological disposal represents the safest long-term option for radioactive waste.

Geological disposal is emplacement of radioactive waste in deep underground formations. The goal of geological disposal is long-term isolation of radioactive waste from our living environment in order to avoid exposure of future generations to ionising radiation from the waste. OPERA (OnderzoeksProgramma Eindberging Radioactief Afval) is the Dutch research programme on geological disposal of radioactive waste.

Within OPERA, researchers of different organisations in different areas of expertise will cooperate on the initial, conditional Safety Cases for the host rocks Boom Clay and Zechstein rock salt. As the radioactive waste disposal process in the Netherlands is at an early, conceptual phase and the previous research programme has ended more than a decade ago, in OPERA a first preliminary or initial safety case will be developed to structure the research necessary for the eventual development of a repository in the Netherlands. The safety case is conditional since only the long-term safety of a generic repository will be assessed. OPERA is financed by the Dutch Ministry of Economic Affairs and the public limited liability company Electriciteits-Produktiemaatschappij Zuid-Nederland (EPZ) and coordinated by COVRA. Further details on OPERA and its outcomes can be accessed at www.covra.nl.

This report concerns a study conducted in the framework of OPERA. The calculations and subsequent analyses presented in this report are part of the in-kind contribution of NRG, and financed by the Ministry of Economic Affairs. The conclusions and viewpoints presented in the report are those of the author(s). COVRA may draw modified conclusions, based on additional literature sources and expert opinions.

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Summary

This report contains the description and the results of long-term safety assessment calculations for the OPERA disposal concept in Boom Clay carried out in the context of OPERA Task 7.3.3: Safety assessment calculations. The calculations presented in this report have been performed by NRG and concern a 'base case' and a selection of four additional subcases identified as part the *Central Assessment Case* (N1) of the *Normal Evolution Scenario* (NES). The results of these simulations will serve as input for the OPERA Safety Case report.

The results of the simulations are presented as graphs and tables, containing a selection of calculated safety and performance indicators, and some observations on these graphs are discussed.

The results reveal within the calculation period of ten million year a peak of the effective dose rate at about 190'000 - 260'000 years after disposal, dependent on the considered subcase. In all subcases, the main contributors to the peak value are the mobile long-lived radionuclides ^{79}Se and ^{129}I. The calculated maximum dose rate is, in all calculated subcases, about one order of magnitude below the reference value of 0.1 mSv/a.

Samenvatting

Dit rapport bevat de beschrijving en de resultaten van berekeningen ter toetsing van de lange-termijn veiligheid van het OPERA-concept in Boomse Klei, uitgevoerd binnen OPERA Taak 7.3.3: Lange-termijn veiligheidstoetsing. De berekeningen zijn uitgevoerd door NRG en betreffen de zogenaamde 'base case' en een viertal parameter variaties van de *Central Assessment Case* (N1), die onderdeel uitmaakt van de *Normal Evolution scenario* (NES). De resultaten van de simulatie dienen als input voor de OPERA Safety Case rapport.

De resultaten van de simulaties zijn gepresenteerd in de vorm van tabellen en grafieken van veiligheids- en prestatie-indicatoren van de OPERA Safety Case, en enkele opmerkingen over het verloop van de curves zijn toegevoegd.

De berekende resultaten laten binnen de rekenperiode van 10 miljoen jaar een maximum voor de effectieve dosis in de biosfeer tussen ongeveer 190'000 - 260'000 jaar na berging zien, afhankelijk van de beschouwde parameter variatie. Voor alle variaties hebben de mobiele, langlevende radionucliden ^{79}Se en ^{129}I de grootste bijdrage aan de maximumwaarde. De piekwaarde is in alle gevallen ongeveer een orde van grootte onder de referentiewaarde van 0,1 mSv/a.

1. Introduction

1.1. Background

The five-year research programme for the geological disposal of radioactive waste –OPERA- started on 7 July 2011 with an open invitation for research proposals. In these proposals, research was proposed for the tasks described in the OPERA Research Plan.

1.2. Objectives

This report contains the description and the results of performance assessment (PA) calculations carried out in the context of OPERA Task 7.3.3: *Safety assessment calculations*. The PA calculations are performed for the *Central Assessment Case* (N1) of the *Normal Evolution Scenario* (NES) that consist of a 'base case' (*DV*) and four subcases (indicated as '*EF*', '*LF*', '*EFLD*', and '*LFLD*'). Note that the current report is only a technical documentation of the PA calculations performed, i.e. it contains no safety statements or discussion on the general context of the cases. This is task of the OPERA Safety Case report (under development).

1.3. Realization

The calculations presented in this report have been performed by NRG and concern five subcases identified as part of the *Central Assessment Case* (N1) of the *Normal Evolution Scenario (NES)*. The calculations were performed applying parameter values as reported in the revision 1 of report OPERA-PU-NRG7251-NES [Schröder, 2017]. One of the calculated cases is based on default parameters values (DV) and is denoted as the '*N1-DV*' case or '*base case*'. In [Verhoef, 2017], four additional subcases with parameter variations of the *Normal Evolution Scenario* from [Schröder, 2017] were selected, which have been subsequently implemented. The calculated results of those variation cases are provided in the present document, too.

1.4. Explanation contents

Chapter 2 contains a short overview of the OPERA *Central Assessment Case* (N1) of the *Normal Evolution Scenario* and provides an overview of the various safety and performance indicators that have been calculated and depicted in this report. For each of the five subcases, Chapter 3 contains the results of safety assessment calculations in form of graphs and tables of the safety and performance indicators selected for the OPERA Safety Case, and some observations on the curves. Conclusions are given in Chapter 4.

2. Case description

2.1. Calculation cases

The Central Assessment Case covers a broad range of future conditions, i.e. various climate conditions (cold, moderate, warm). Furthermore, since no site location has yet been established, the considered parameter values determining the radionuclide adsorption capacity of the host formation have to cover broad ranges. These ranges are addressed by defining subcases. Table 2-1 provides an overview of all subcases identified as part of the *Central Assessment case* N1 of the *Normal Evolution Scenario* [Schröder, 2017, Table 8-1].

Table 2-1 Subcases identified as part of the *central assessment case* N1 of the *Normal evolution scenario*.

Compartment	Subcases	
Waste-EBS	• *Failure base case (**DV**)* • *Early container failure case (**EF**)* • *Late container failure case (**LF**)*	
	• *Release base case (**DV**)* • *Slow release case (**SR**)* • *Fast release case (**FR**)*	
	• *Solubility base case (**DV**)* • *Low solubility case (**LS**)*	
Host rock	• *Base case (**DV**)* • *High DOC case (**HD**)* • *Low DOC case (**LD**)*	
Overburden	• *Fast streamline (**DV**)* • *Medium streamline (**MS**)* • *Slow streamline (**SS**)*	
	• *Little dispersion case (**DV**)* • *Intermediate dispersion case (**ID**)* • *Large dispersion case (**LaD**)*	
	• *Present day climate (**DV**) ** • *Cold climate without ice cover (permafrost) (**BC**) *** • *Cold climate with ice cover (glaciation) (**GC**)* • *Warm climate, climate change prediction WH of KNMI (**CM2**)* • *Warm climate, Mediterranean climate (**CM**) ****	
Biosphere	• *Temperate climate case (**DV**)* • *Mediterranean climate case (**CM**)* • *Boreal climate case (**BC**)*	
	• *Drinking water well case (**DW**)*	• *Regional pumping station case (**DW-R**)* • *Local well case (**DW-L**)*
	• *Irrigation water well case(**IW**)*	• *Regional pumping station case (**IW-R**)* • *Local well case (**DV**)*
	• *Rivers or lakes case (**RL**)*	• *Large river case (**RL-L**)* • *Small river case (**RL-S**)*
	• *Wetland case (**WL**)*	• *Vertical flow case (**WL-V**)* • *Horizontal flow case (**WL-H**)*

* comparable to the *Temperate climate case* in the *Biosphere*
** comparable to the *Boreal climate case* in the *Biosphere*
*** comparable to the *Mediterranean climate case* in the *Biosphere*

In [Verhoef, 2017] it was decided to focus the Safety Assessment on the *Central Assessment case* (N1) of the *Normal Evolution Scenario* (NES), and to cover part of the potential variations by calculating a base case and four additional subcases. Table 2-2 provides an overview of selected subcases analysed in the current report, as part of the Central Assessment case of the Normal Evolution Scenario (see Table 2-1 above).

Table 2-2 Overview of cases to be analysed in the OPERA safety assessment (DOC = dissolved organic carbon).

Case Id	Waste-EBS	$T_{failure}$ (a)	Host Rock	DOC concentration (mg/l)
DV	Supercontainer failure base case (DV)	35'000	DOC base Case (DV)	100
EF	Early Supercontainer failure (EF)	1'000	DOC base Case (DV)	100
LF	Late Supercontainer failure (LF)	70'000	DOC base Case (DV)	100
EFLD	Early Supercontainer failure (EF)	1'000	Low DOC Case (LD)	20
LFLD	Late Supercontainer failure (LF)	70'000	Low DOC Case (LD)	20

2.2. Indicators and calculation methodology

An overview on the overall set of indicators proposed for the OPERA Safety Case, as well as the calculation methodology is given in [Schröder, 2016]. Additional indicators are proposed in [Neeft, 2017] and a small number of alternative indicator representations were prepared in order to provide a more focussed representation of the OPERA calculation outcomes (P4e and P14 in Table 2-4).

Table 2-3 and Table 2-4 below show an overview of all indicators, the link of the indicators to the considered compartments as well as the identifier of these indicators to be used when reporting the calculations results.

Table 2-3 Safety indicators for the OPERA Safety Case.

Safety indicator	compartments	unit	identifier
Effective dose rate	*Biosphere*	Sv/a	S1
Radiotoxicity concentration in biosphere water	*Biosphere water*	Sv/m^3	S2
Radiotoxicity flux from geosphere	*Overburden*	Sv/a	S3

Table 2-4 Proposed performance indicators for the OPERA Safety Case.

Performance indicator	compartments	units	identifier
Radiotoxicity in compartments	*Waste-EBS*, *Host Rock*, *Overburden*	Sv	P1a - P1c
Radiotoxicity flux from compartments	*Waste-EBS* to *Host Rock*, *Host Rock* to *Overburden*, *Overburden* to *Biosphere*	Sv/a	P2a - P2c
Time-integrated radiotoxicity flux from compartments	*Waste-EBS* to *Host Rock*, *Host Rock* to *Overburden*, *Overburden* to *Biosphere*	Sv	P3a - P3c
Radiotoxicity concentration in compartment water	*Waste-EBS*, *Host Rock*, *Overburden*	Sv/m^3	P4a - P4c
Fractional radiotoxicity in compartments	*Waste-EBS (contained and non-contained)*, *Host Rock*, *Overburden*	-	P4e
Host rock confinement factor	*Overburden*, *Host formation*	-	P5
Transport time through compartments	*Biosphere*, *Biosphere water*, *Overburden* to *Biosphere*	Sv	P6a en P6b
Contribution of each (barrier) compartment	*Performance indicator based on safety functions*	%	P7
Activity concentration in *Biosphere* water	*Biosphere*	Bq/m^3	P8
Activity concentration in uppermost and lower *Overburden cell*	*Overburden*	Bq/m^3	P9 & P10
Activity concentration in uppermost and lower *Host Rock cell*	*Host Rock*	Bq/m^3	P11 & P12
Radiotoxicity flux from *Waste-EBS* compartment	*Vitrified HLW* to *Host Rock*, *Spent Fuel* to *Host Rock*, *Non-heat-generating HLW* to *Host Rock*, *Depleted Uranium* to *Host Rock*, *LILW* to *Host Rock*	Sv/a	P13a - P13e
Contribution to overall safety	*Waste-EBS*, *Host Rock*, *Overburden*	%	P14
Containment (C-RT)	*Waste-EBS*	-	BI1
Limitation of release (R1-RT)	*Waste-EBS* to *Host Rock*, *Waste-EBS*	-	BI2
Retardation due to migration through host formation (R3 - RT)	*Host Rock* to *Overburden*, *Waste-EBS* to *Host Rock*,	-	BI3
Retardation due to migration through overburden (R4 - RT)*	*Overburden* to *Biosphere*, *Host Rock* to *Overburden*,	-	BI4
Performance of the integrated repository system (IRS-RT)	*Waste-EBS (contained and non-contained)*, *Host Rock*, *Overburden*, *Biosphere*	-	BI5

** This only applies to the residence times in the aquifer in the surrounding rock formations.

For the definition of the indicators, the following nomenclature is used:

- *Radionuclides* are numbered by *n*
- The *ingestion dose coefficient* $e(50)_n$ is the dose caused by ingestion of radionuclide *n* [Sv per Bq intake]. The ingestion dose coefficients for adults, which correspond to the committed effective dose integrated over 50 years, are used [VROM 2001, Appendix 4, Table 4.1]. The effects of radioactive daughter nuclides produced in vivo are accounted for.

- The *biosphere dose conversion factor* DCF_n is the annual dose to the most exposed members of the public (so-called critical group) caused by a unit concentration of radionuclide *n* in the biosphere water. It is measured in [(Sv/a)/(Bq/m^3)]. It takes into account various exposure pathways as well as living and nutrition habits. Biosphere dose conversion factors are provided by the biosphere analyses, following the guidance given in national regulations where available.
- c_n is the *activity concentration* [Bq/m^3] of radionuclide *n* in the biosphere water
- s_n is the *activity flux*[1] [Bq/a] of radionuclide *n* from the geosphere to the biosphere
- $a_{n,i}$ is the *activity* [Bq] of radionuclide *n* in compartment *i*
- $a'_{n,i}$ is the *activity* [Bq] of radionuclide *n*, contained in waste compartment *i*
- $c_{n,i}$ is the average *activity concentration* [Bq/m^3 of water] of radionuclide *n* in the water of compartment *i*
- $s_{n,i}$ is the *activity flux*[1] [Bq/a] of radionuclide *n* released from compartment *i*
- $(a_{n,i})_t$ is the *activity* [Bq] of radionuclide *n* in compartment *i* on time step *t*
- E_n is the decay energy of a radionuclide *n*

In [Verhoef, 2017], it was agreed that for the interpretation and communication of the Safety Case only a limited number of indicators is needed:
- *Effective dose rate in the biosphere*
- *Radiotoxicity concentration in biosphere water*
- *Barrier performance indicator*

The outcomes of the safety assessment calculations reported in the following sections have therefore been limited to the selected set of indicators.

[1] Note that although generally *flux* is defined as the rate of *flow* of a property per unit area, here we follow the definitions as used in the literature on safety and performance indicators.

3. Calculations results

3.1. Central Assessment Case (N1-DV)

This section presents the results of the simulation of the Central Assessment Case N1-DV. The calculations were performed applying agreed default parameter values (DV) in the *Central Assessment Case* (N1) of the *Normal Evolution Scenario* as reported in revision 1 of report OPERA-PU-NRG7251-NES [Schröder, 2017].

The results show that a limited number of radionuclides are relevant for assessing the system behaviour. These nuclides and their origin (waste type) are summarized in Table 3-1.

3.1.1. Effective dose rate (S1)

The effective dose rate represents the annual individual effective dose to an average member of the group of the most exposed individuals. It takes into account dilution and accumulation in the biosphere, various exposure pathways as well as living and nutrition habits.

$$\textit{Effective dose rate [Sv/a]} = \sum_{\textit{all nuclides}} c_n DCF_n \qquad \textit{Equation 1}$$

The effective dose rate is represented in three manners:

- as sum of all nuclides and the most relevant contributing nuclides (Figure 3-1),
- as sum of all disposal sections and the contribution of the five disposal sections (Figure 3-2), and
- as sum of all nuclides and contribution of the four natural nuclides chains (Figure 3-3).

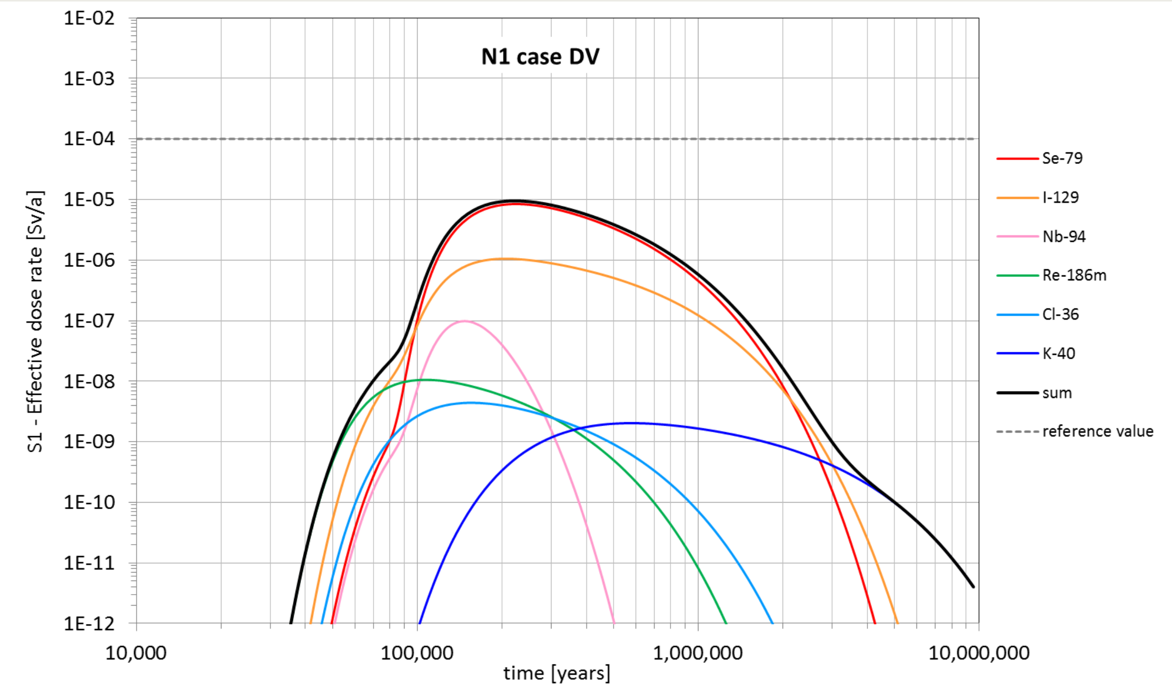

Figure 3-1 Effective dose rate (S1). Calculation case N1-DV. PA model version 9.3.

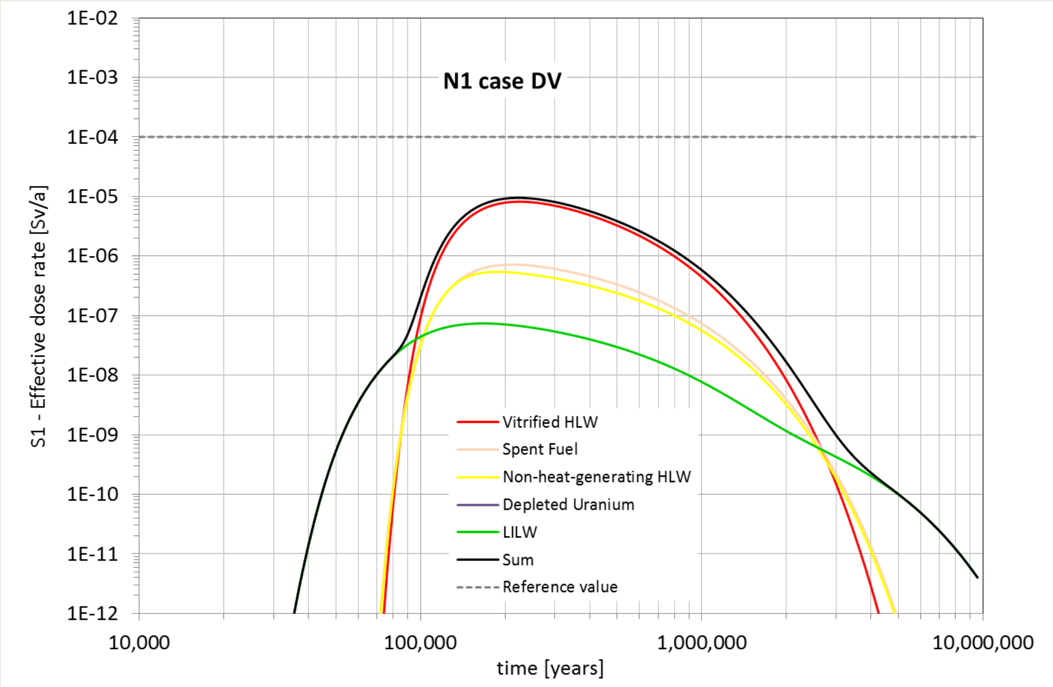

Figure 3-2 Contribution of the various disposal sections to the effective dose rate (S1). Calculation case N1-DV. PA model version 9.3.

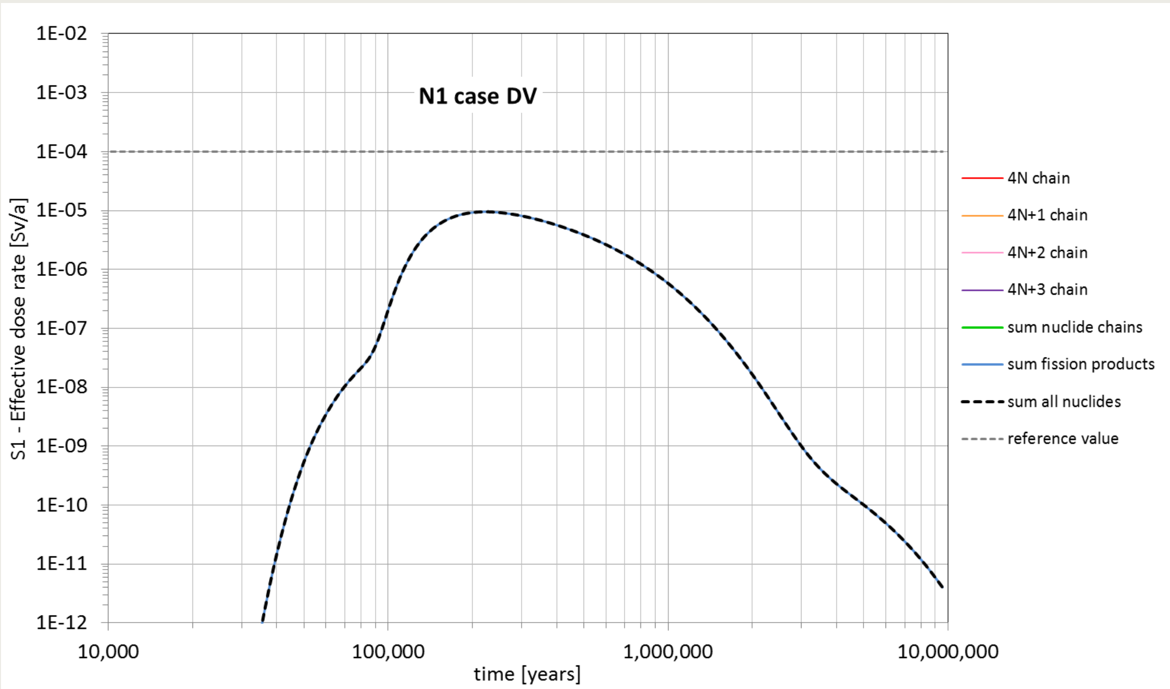

Figure 3-3 Contribution of the natural nuclide decay chains to the effective dose rate (S1). Calculation case N1-DV. PA model version 9.3.

Table 3-1 Maximum values Effective dose rate (S1). Calculation case N1-DV. PA model version 9.3.

Nuclide	*Time [a]*	*Dose Rate [Sv/a]*	*Predominant origin*
Se-79	2.29E+05	8.43E-06	Vitrified HLW
I-129	2.09E+05	1.06E-06	Spent Fuel / Non-heat-generating HLW
Nb-94	1.45E+05	9.79E-08	Non-heat-generating HLW
Re-186m	1.05E+05	1.06E-08	LILW
Cl-36	1.58E+05	4.40E-09	LILW
K-40	5.75E+05	2.03E-09	LILW
Sum	**2.19E+05**	**9.51E-06**	

Observations:

- The calculated maximum dose rate results from radionuclides from the 4 waste sections (in order) *Vitrified HLW*, *Spent Fuel*, *Non-heat-generating HLW*, and *LILW (*dominating on early time steps and the very long term*)*
- The maximum is dominated by the contributions of ^{79}Se, from the CSD-V containers, and ^{129}I from the Spent Fuel and CSD-C containers
- The maximum dose rate (9.5 μSv/a) is about one order of magnitude below the reference value for the dose rate (0.1 mSv/a)
- Within the assessment period of 10 Ma, the contribution of the four natural nuclide chains to the effective dose rate is negligible (way below scale)

3.1.2. Radiotoxicity concentration in biosphere water (S2)

This indicator, expressed in [Sv/m^3], represents the radiotoxicity of the radionuclides in 1 m^3 of biosphere water. It can also be interpreted as the dose rate resulting by drinking of 1 m^3 of biosphere water containing the radionuclides under consideration.

$$\textit{Radiotoxicity concentration in biosphere water [Sv/m}^3\textit{]} = \sum_{all\ nuclides} c_n e(50)_n \qquad \textit{Equation 2}$$

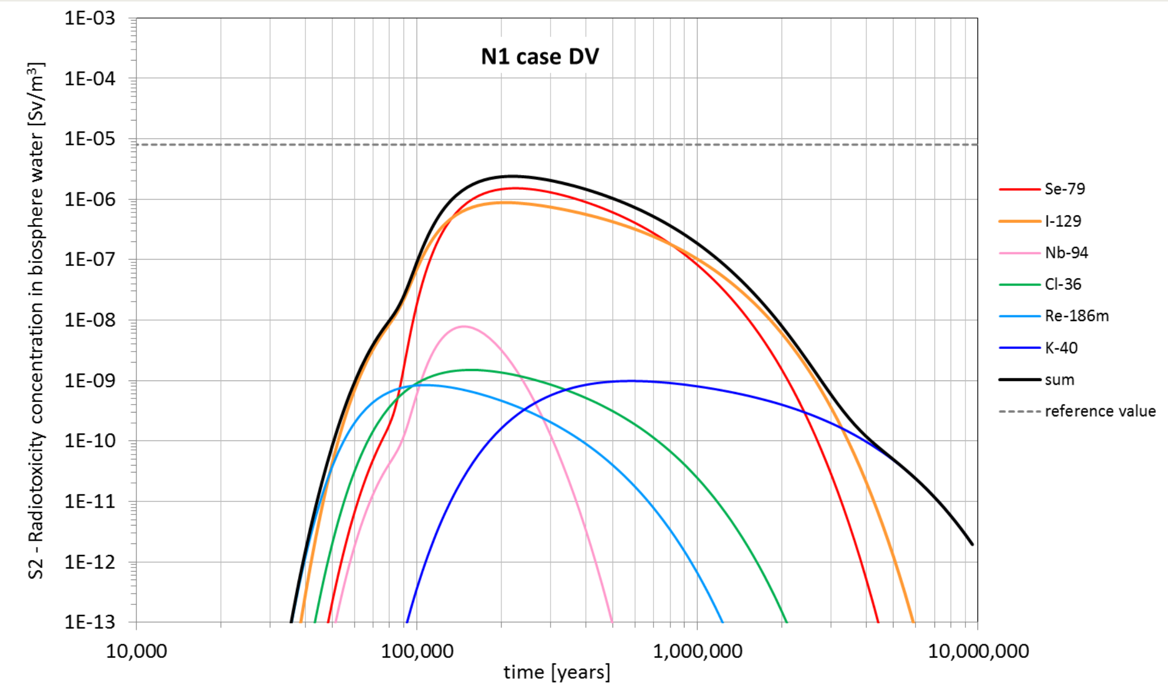

Figure 3-4 Radiotoxicity concentration in biosphere water (S2). Calculation case N1-DV. PA model version 9.3.

Table 3-2 Maximum values Radiotoxicity concentration in biosphere water (S2). Calculation case N1-DV. PA model version 9.3.

Nuclide	*Time [a]*	*Radiotoxicity concentration [Sv/m^3]*
Se-79	2.29E+05	1.52E-06
I-129	2.09E+05	8.79E-07
Nb-94	1.45E+05	7.82E-09
Cl-36	1.58E+05	1.50E-09
K-40	5.75E+05	9.85E-10
Re-186m	1.05E+05	8.41E-10
Sum	**2.19E+05**	**2.40E-06**

Observations:

- The same dominant radionuclides appear as for the dose rate (S1), but in some cases in a different order with respect to their relative contribution. The difference is caused by the use of other Dose Conversion Factors (DCC): DCCs for ingestion instead of biosphere weighted DCCs.

3.1.3. Performance of the integrated repository system (BI5)

Figure 3-5 shows the overall barrier performance provided by the repository system, and the (time-dependent) contribution of each of the barriers. The indicator represents a kind of ‘risk dilution’ indicator, i.e. a low value means a good performance, and a value of 1 means no contribution to the safety at all. The indicator *BI5*, *Integrated performance*, summarizes the indicators *BI1* to *BI4* [Schröder, 2016] and is calculated by multiplying the values of *BI1* to *BI4* at each time step.

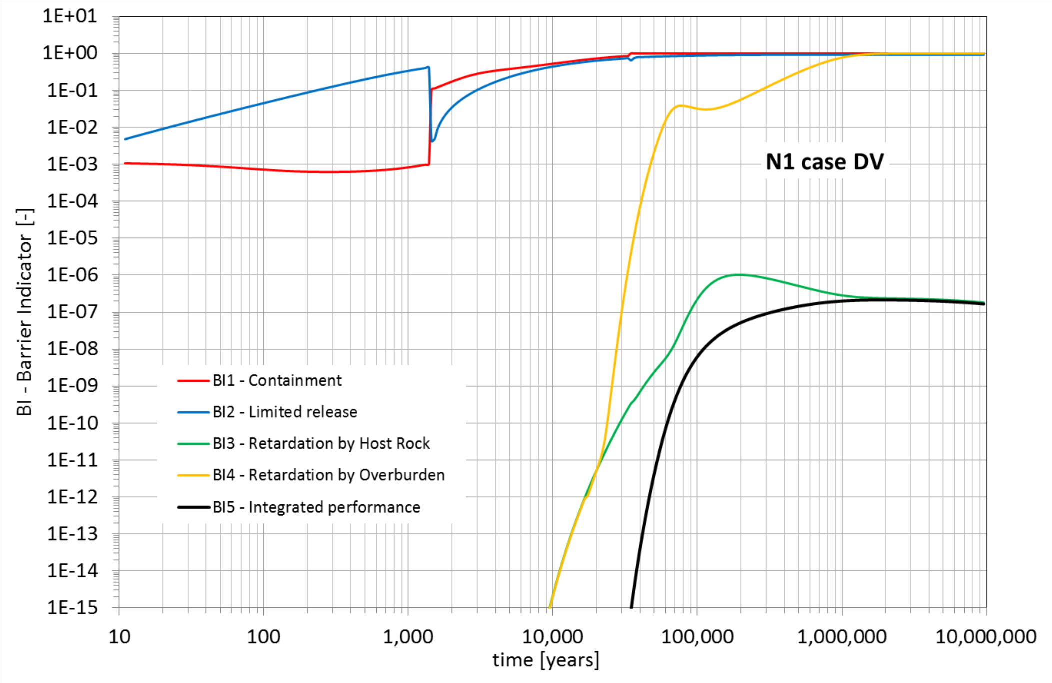

Figure 3-5 Performance of the integrated repository system (BI5). Calculation case N1-DV. PA model version 9.3.

Observations:

- The indicators *BI1* and *BI2* show that - compared to the host rock - the safety provided by the engineered barriers for the N1 case is limited, both in time, and in the overall extent.
- The integrated performance of the OPERA disposal system is mainly determined by the retardation of radionuclides in the host rock, as indicated by *BI3*
- Although not considered a safety barrier, the indicator *BI4* shows that the overburden still contributes significant to the overall safety for periods smaller than the residence time

3.1.4. Fractional radiotoxicity in compartments (P4e)

Another variant of a barrier performance indicator can be derived from indicator *P4* (Schröder, 2016) by plotting the relative amounts of the total radiotoxicity present in the various compartments:

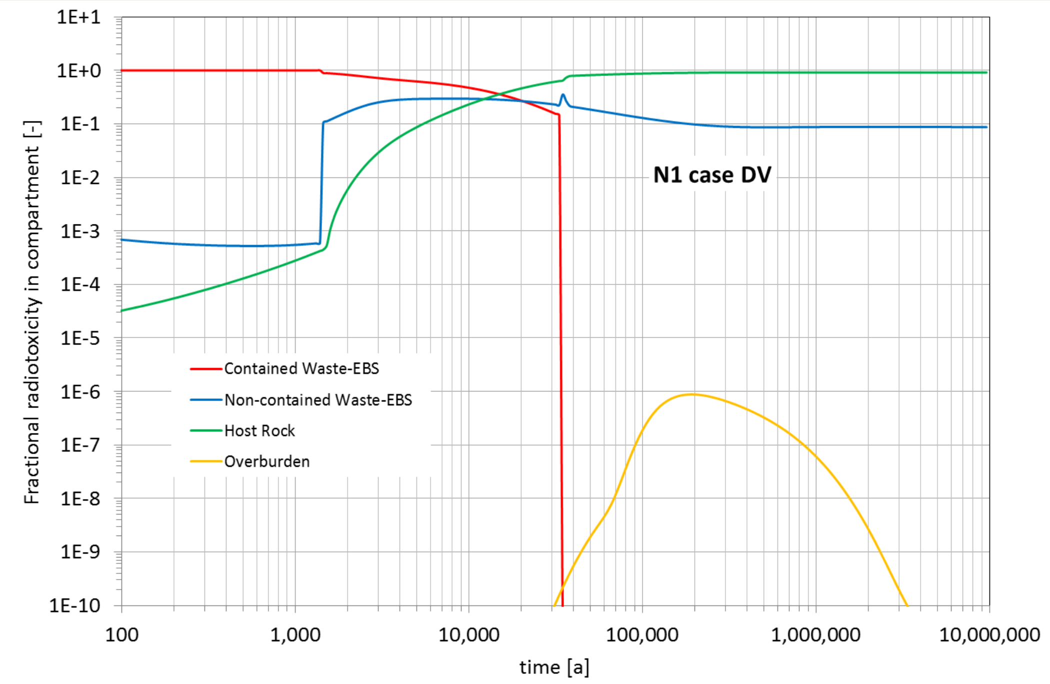

Figure 3-6 Fractional radiotoxicity of the different compartments of the repository system. Calculation case N1-DV. PA model version 9.3.

Observations:

- Before the failure of the supercontainers (35’000 a), a large fraction of the radiotoxicity is safely isolated in these containers (“Contained Waste-EBS”)
- After the failure of the supercontainers (35’000 a), still a significant fraction (> ca. 10%) of the total radiotoxicity remains - although uncontained - in the *Waste-EBS* compartment
- After the failure of the supercontainers (35’000 a), the host rock contains the largest radiotoxicity fraction (80%, increasing to about 90% in the long term)
- The radiotoxicity fraction in the overburden remains at least 6 orders of magnitude below the fraction in the host rock

3.2. Early container failure (EF)

This section presents the results of the simulation of the *Early container failure* subcase of the *Central Assessment Case* of the *Normal evolution scenario* (N1-EF). Also in this subcase, only a limited number of radionuclides determine the system behaviour.

3.2.1. Effective dose rate (S1)

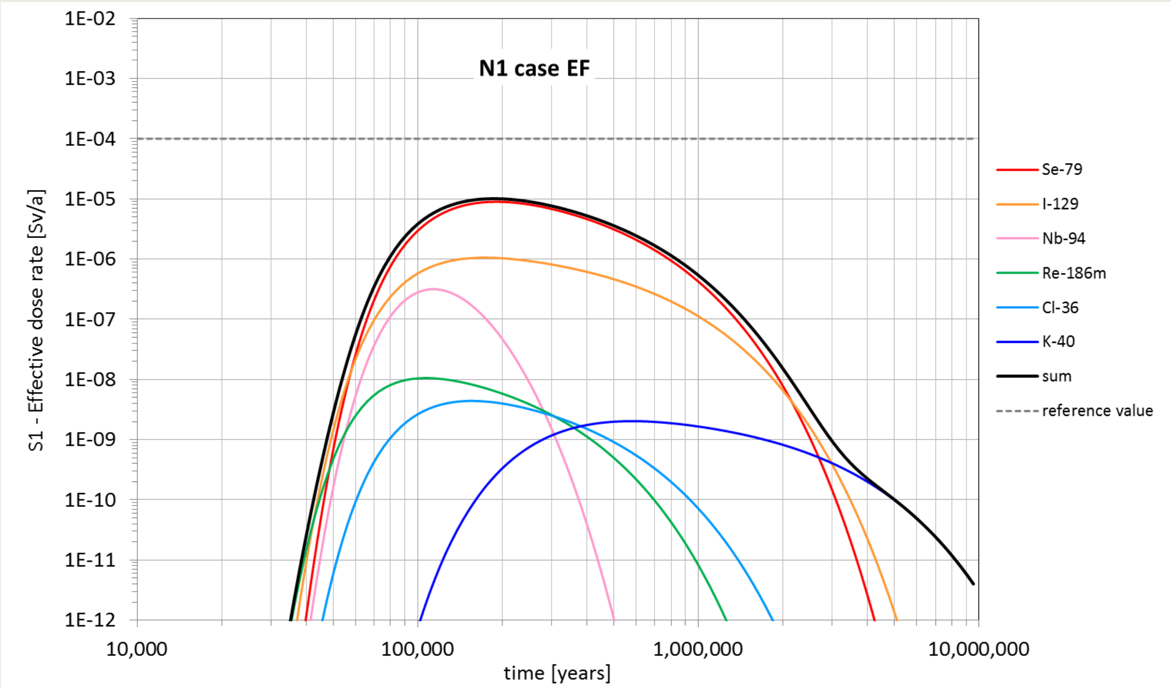

Figure 3-7 Effective dose rate (S1). Calculation case N1-EF. PA model version 9.3.

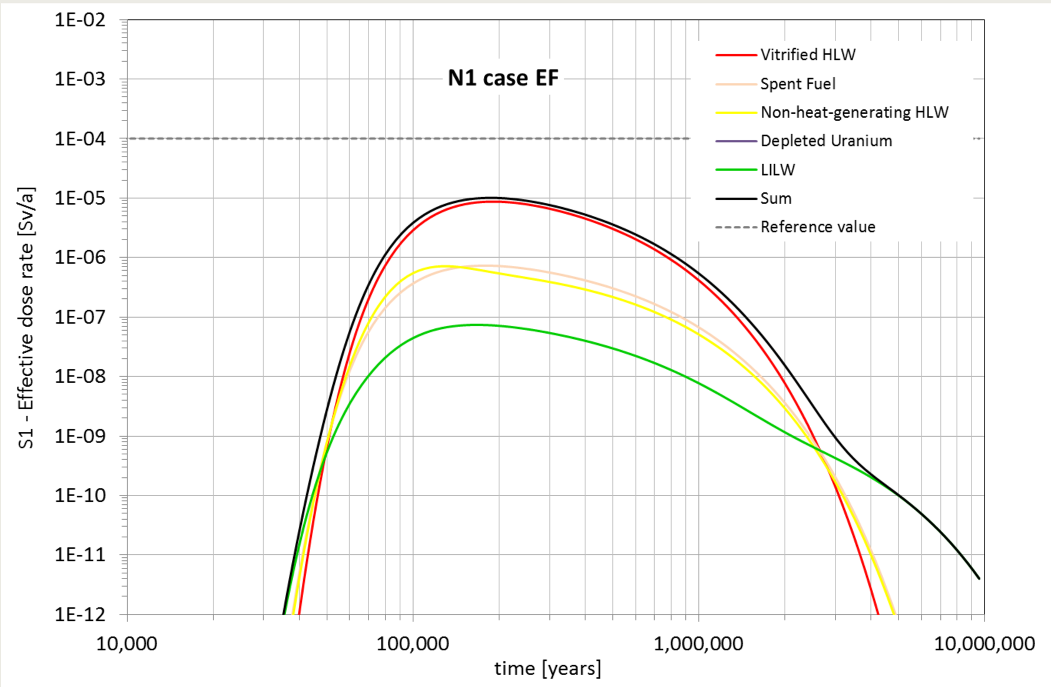

Figure 3-8 Contribution of the various disposal sections to the effective dose rate (S1). Calculation case N1-EF. PA model version 9.3.

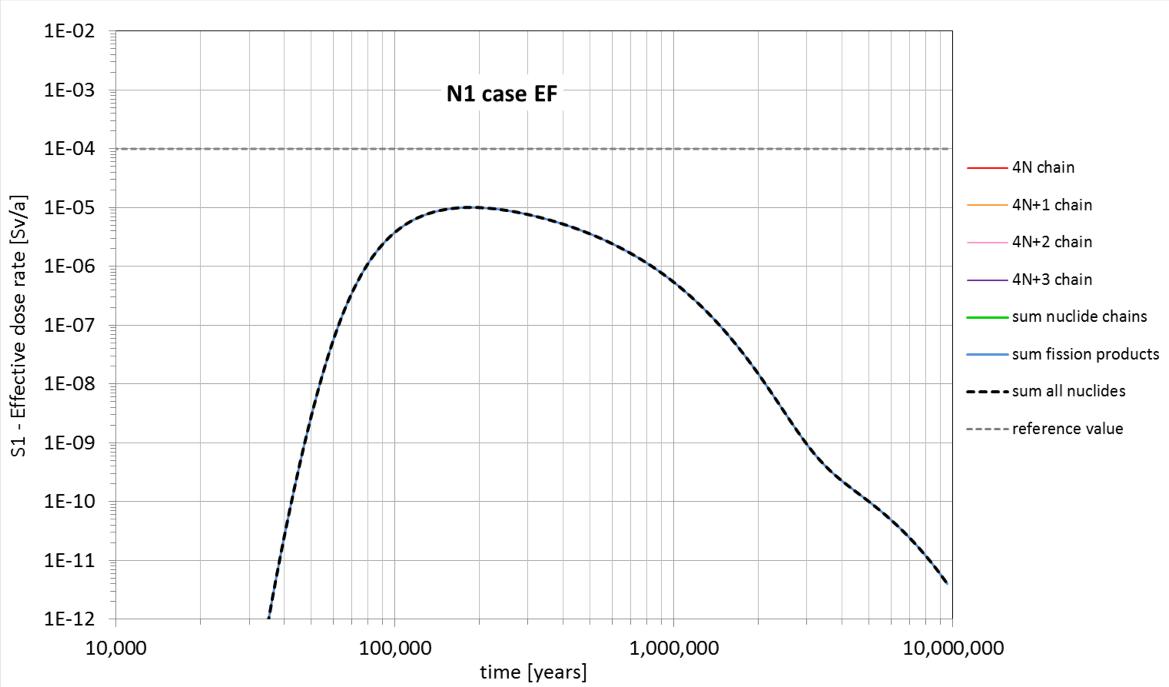

Figure 3-9 Contribution of the natural nuclide decay chains to the effective dose rate (S1). Calculation case N1-EF. PA model version 9.3.

Table 3-3 Maximum values Effective dose rate (S1). Calculation case N1-EF. PA model version 9.3.

Nuclide	***Time [a]***	***Dose Rate [Sv/a]***	***Predominant origin***
Se-79	1.91E+05	8.98E-06	Vitrified HLW
I-129	1.74E+05	1.06E-06	Spent Fuel / Non-heat-generating HLW
Nb-94	1.15E+05	3.17E-07	Non-heat-generating HLW
Re-186m	1.05E+05	1.06E-08	LILW
Cl-36	1.58E+05	4.40E-09	LILW
K-40	5.75E+05	2.03E-09	LILW
Sum	**1.91E+05**	**1.01E-05**	

Observations:

- The early failure subcase is very comparable to the base case, with the maximum dose rate occurring somewhat earlier (190’000 instead of 220’000 years).
- The contribution of LILW in the early phase is less visible due to the earlier container failure in the HLW-sections.
- The maximum is dominated by the contributions of ^{79}Se, from the CSD-V containers, and ^{129}I from the Spent Fuel and CSD-C containers
- The maximum dose rate (10 µSv/a) is about one order of magnitude below the reference value for the dose rate (0.1 mSv/a)
- Within the assessment period of 10 Ma, the contribution of the four natural nuclide chains to the effective dose rate is negligible (way below scale)

3.2.2. Radiotoxicity concentration in biosphere water (S2)

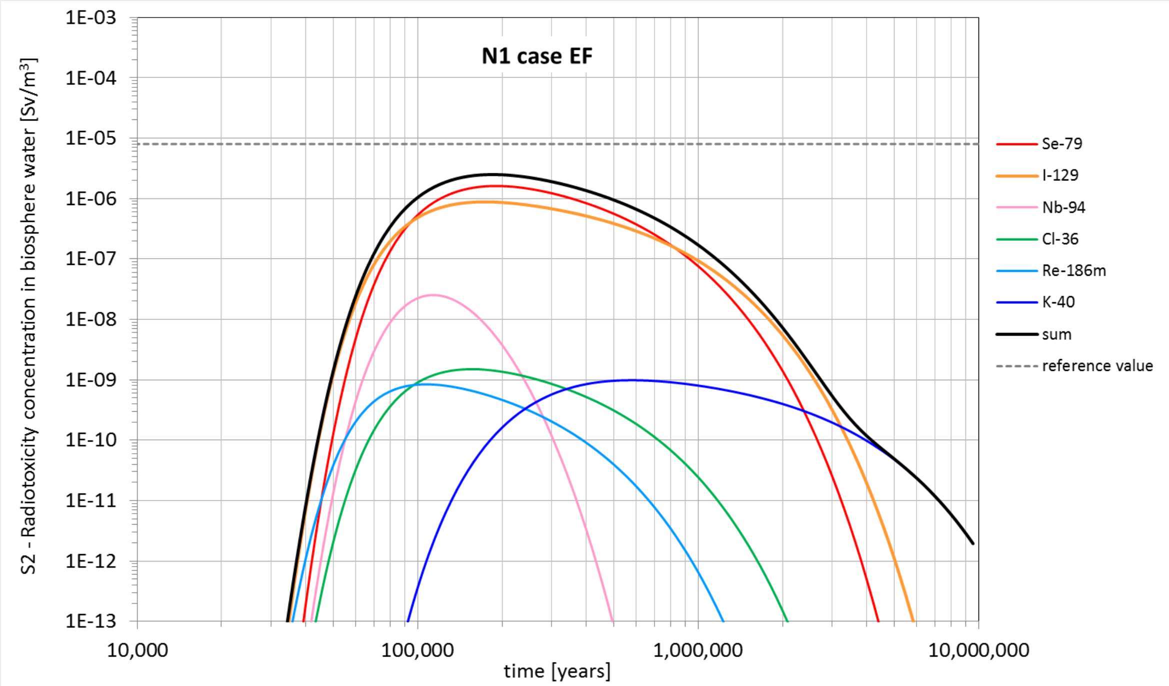

Figure 3-10 Radiotoxicity concentration in biosphere water (S2). Calculation case N1-EF. PA model version 9.3.

Table 3-4 Maximum values Radiotoxicity concentration in biosphere water (S2). Calculation case N1- N1-EF. PA model version 9.3.

Nuclide	***Time [a]***	***Radiotoxicity concentration [Sv/m³]***
Se-79	1.91E+05	1.62E-06
I-129	1.74E+05	8.82E-07
Nb-94	1.15E+05	2.53E-08
Cl-36	1.58E+05	1.50E-09
K-40	5.75E+05	9.85E-10
Re-186m	1.05E+05	8.41E-10
Sum	1.82E+05	2.50E-06

Observations:

- Like in the base case, the same dominant radionuclides appear as for the dose rate (S1), but in some cases in a different order with respect to their relative contribution. The difference is caused by the use of other Dose Conversion Factors (DCC): DCCs for ingestion instead of biosphere weighted DCCs.

3.2.3. Performance of the integrated repository system (BI5)

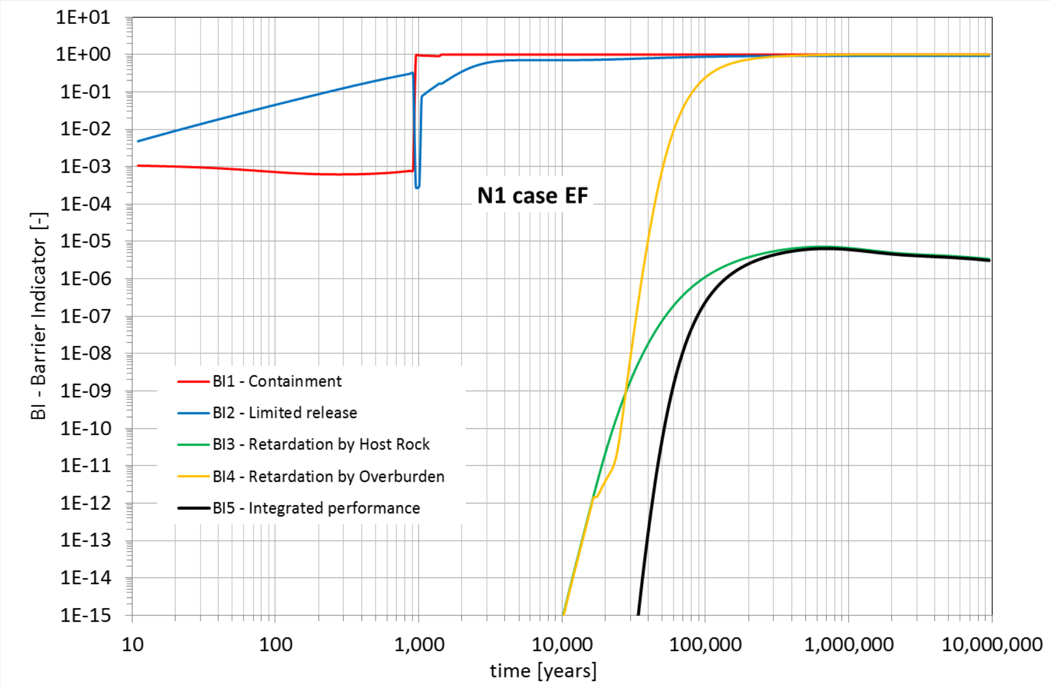

Figure 3-11 Performance of the integrated repository system (BI5). Calculation case N1-EF. PA model version 9.3.

Observations:

- Like for the base case, the indicators *BI1* and *BI2* show that the safety provided by the engineered barriers for the N1 case is limited, both in time, and in the overall extent, compared to the safety provided by the host rock
- The integrated performance of the OPERA disposal system is mainly determined by the retardation of radionuclides in the host rock, as indicated by *BI3*
- Although not considered a safety barrier, the indicator *BI4* shows that the overburden still contributes significant to the overall safety for periods smaller than the residence time.

3.2.4. Fractional radiotoxicity in compartments (P4e)

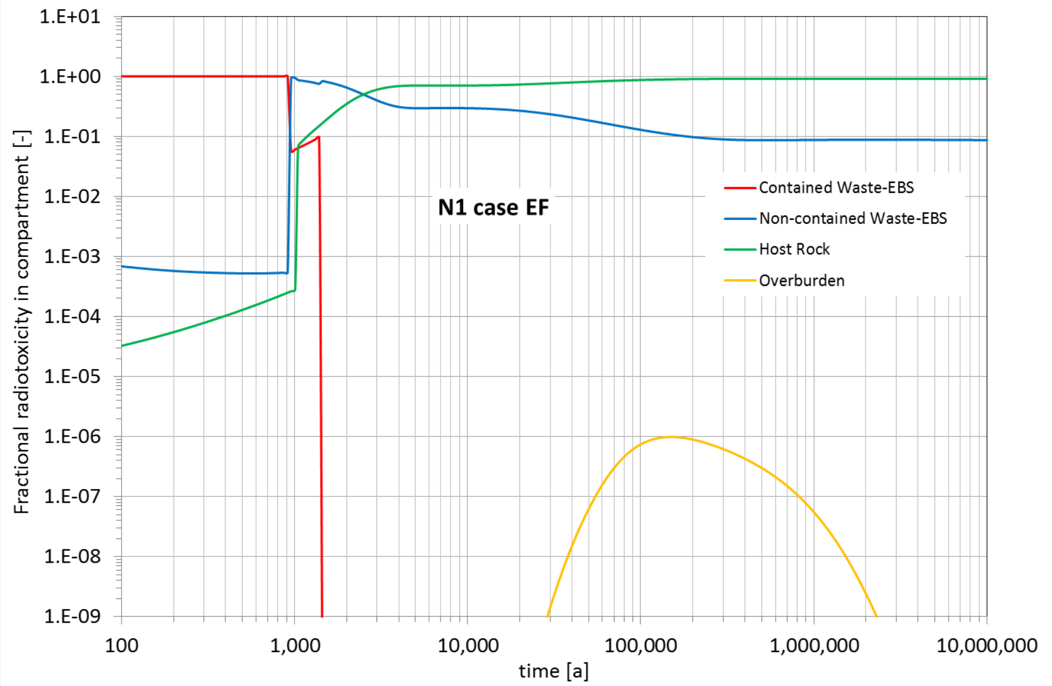

Figure 3-12 Fractional radiotoxicity of the different compartments of the repository system. Calculation case N1-EF. PA model version 9.3.

Observations:

- Before the failure of the supercontainers (1000 a), a large fraction of the radiotoxicity is safely isolated in these containers ("Contained Waste-EBS")
- Between the failure of the supercontainers (1000) and the failure of the Konrad containers containing depleted uranium (1500 a) a significant fraction (> ca. 10%) of the total radiotoxicity remains contained in the *Waste-EBS* compartment
- After the failure of the supercontainers (1000 a) and Konrad containers (1500 a), still a significant fraction (> ca. 10%) of the total radiotoxicity remains - although uncontained - in the *Waste-EBS* compartment
- After 2500 a, the host rock contains the largest radiotoxicity fraction
- The radiotoxicity fraction in the overburden remains at least 6 orders of magnitude below the fraction in the host rock

3.3. Late container failure (LF)

This section presents the results of the simulation of the *Late container failure* subcase of the *Central Assessment Case* of the *Normal evolution scenario* (N1-LF). As in the previous subcases, a limited number of radionuclides are relevant for assessing the system behaviour.

3.3.1. Effective dose rate (S1)

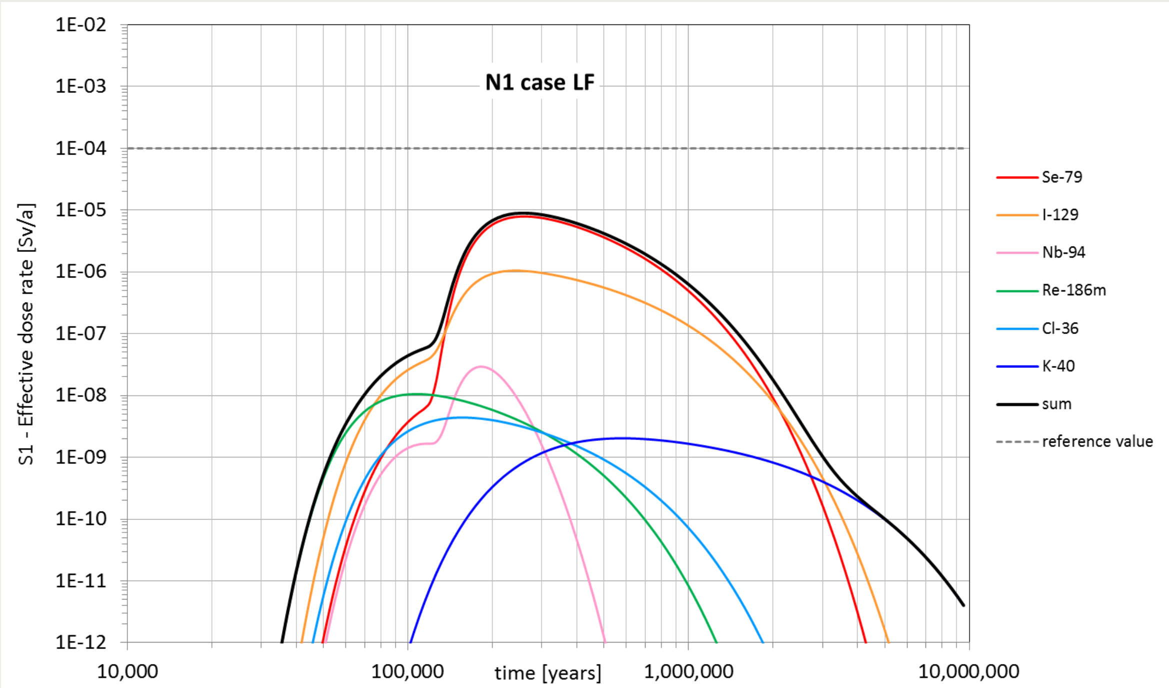

Figure 3-13 Effective dose rate (S1). Calculation case N1-LF. PA model version 9.3.

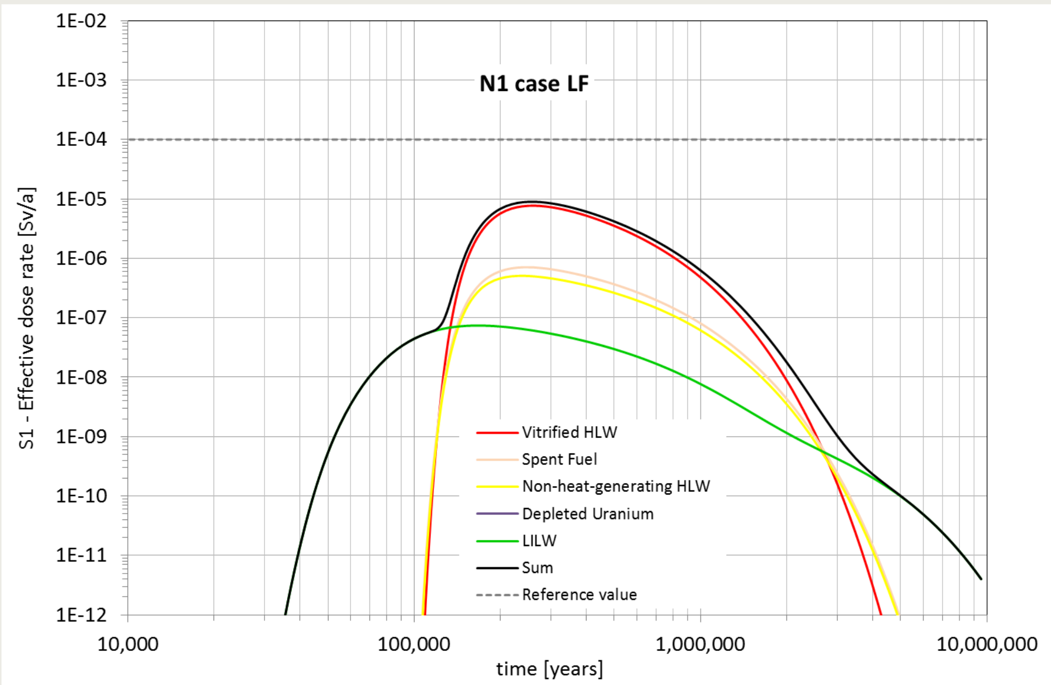

Figure 3-14 Contribution of the various disposal sections to the effective dose rate (S1). Calculation case N1-LF. PA model version 9.3.

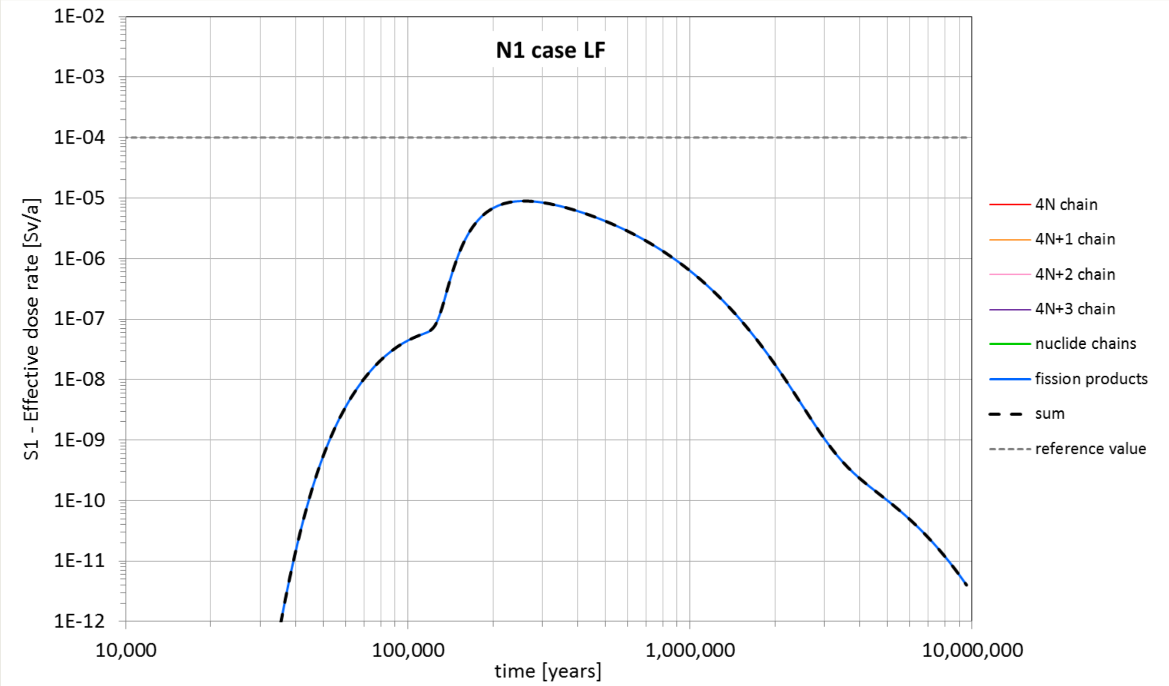

Figure 3-15 Contribution of the natural nuclide decay chains to the effective dose rate (S1). Calculation case N1-LF. PA model version 9.3.

Table 3-5 Maximum values Effective dose rate (S1). Calculation case N1-LF. PA model version 9.3.

Nuclide	*Time [a]*	*Dose Rate [Sv/a]*	*Predominant origin*
Se-79	2.63E+05	7.91E-06	Vitrified HLW
I-129	2.40E+05	1.05E-06	Spent Fuel / Non-heat-generating HLW
Nb-94	1.82E+05	2.94E-08	Non-heat-generating HLW
Re-186m	1.05E+05	1.06E-08	LILW
Cl-36	1.58E+05	4.40E-09	LILW
K-40	5.75E+05	2.03E-09	LILW
Maximum	**2.63E+05**	**8.95E-06**	

Observations:

- The *Late container failure* subcase is very comparable to the base case, with the maximum value occurring somewhat later (260’000 instead of 220’000 years).
- The contribution of LILW in the early phase is more pronounced due to the later container failure in the HLW-sections.
- The maximum is dominated by the contributions of ^{79}Se, from the CSD-V containers, and ^{129}I from the Spent Fuel and CSD-C containers
- The maximum dose rate (9 µSv/a) is about one order of magnitude below the reference value for the dose rate (0.1 mSv/a)
- Within the assessment period of 10 Ma, the contribution of the four natural nuclide chains to the effective dose rate is negligible (way below scale)

3.3.2. Radiotoxicity concentration in biosphere water (S2)

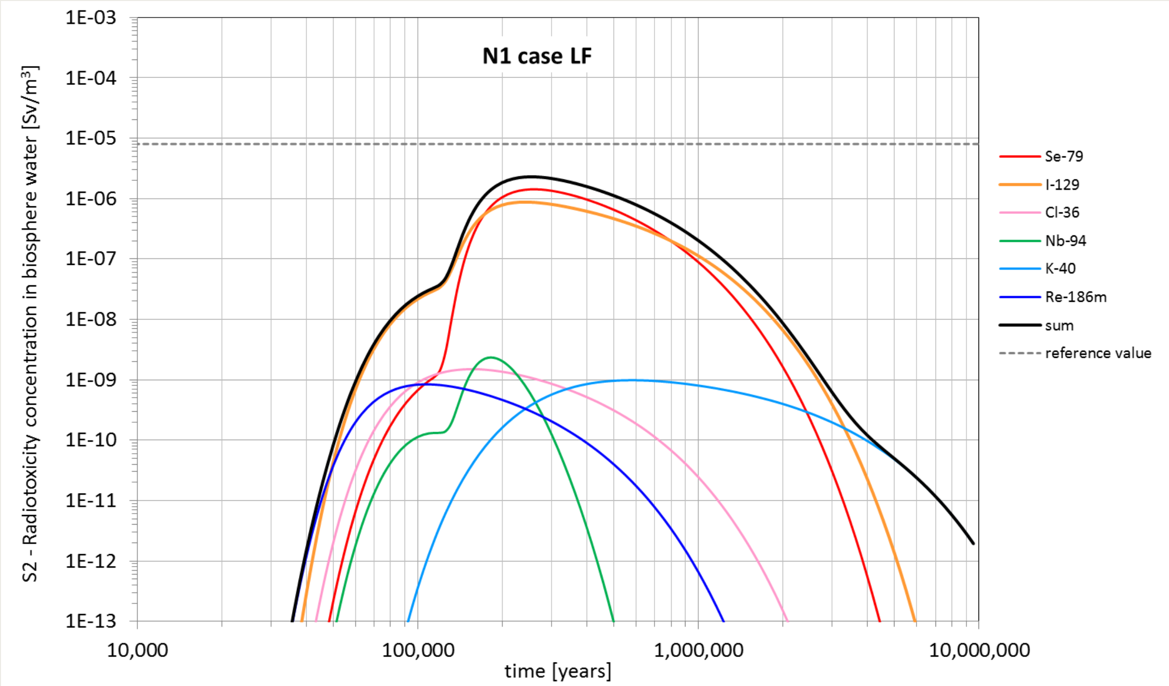

Figure 3-16 Radiotoxicity concentration in biosphere water (S2). Calculation case N1-LF. PA model version 9.3.

Table 3-6 Maximum values Radiotoxicity concentration in biosphere water (S2). Calculation case N1-LF. PA model version 9.3.

Nuclide	***Time [a]***	***Radiotoxicity concentration [Sv/m³]***
Se-79	2.63E+05	1.42E-06
I-129	2.40E+05	8.75E-07
Nb-94	1.82E+05	2.34E-09
Cl-36	1.58E+05	1.50E-09
K-40	5.75E+05	9.85E-10
Re-186m	1.05E+05	8.41E-10
Maximum	**2.51E+05**	**2.29E-06**

Observations:

- Like in the base case, the same dominant radionuclides appear as for the dose rate (S1), but in some cases in a different order with respect to their relative contribution. The difference is caused by the use of other Dose Conversion Factors (DCC): DCCs for ingestion instead of biosphere weighted DCCs.

3.3.3. Performance of the integrated repository system (BI5)

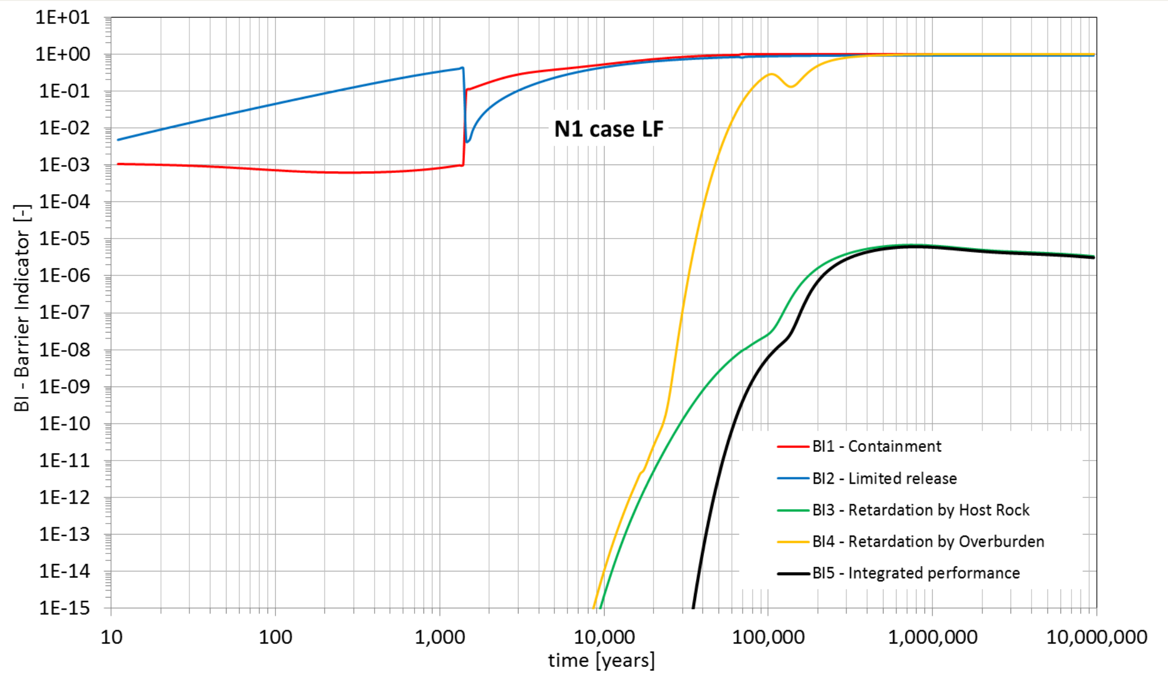

Figure 3-17 Performance of the integrated repository system (BI5). Calculation case N1-LF. PA model version 9.3.

Observations:

- Like for the base case, the indicators *BI1* and *BI2* show that the safety provided by the engineered barriers for the N1 case is limited, both in time, and in the overall extent, compared to the safety provided by the host rock
- The integrated performance of the OPERA disposal system is mainly determined by the retardation of radionuclides in the host rock, as indicated by *BI3*
- Although not considered a safety barrier, the indicator *BI4* shows that the overburden still contributes significant to the overall safety for periods smaller than the residence time.

3.3.4. Fractional radiotoxicity in compartments (P4e)

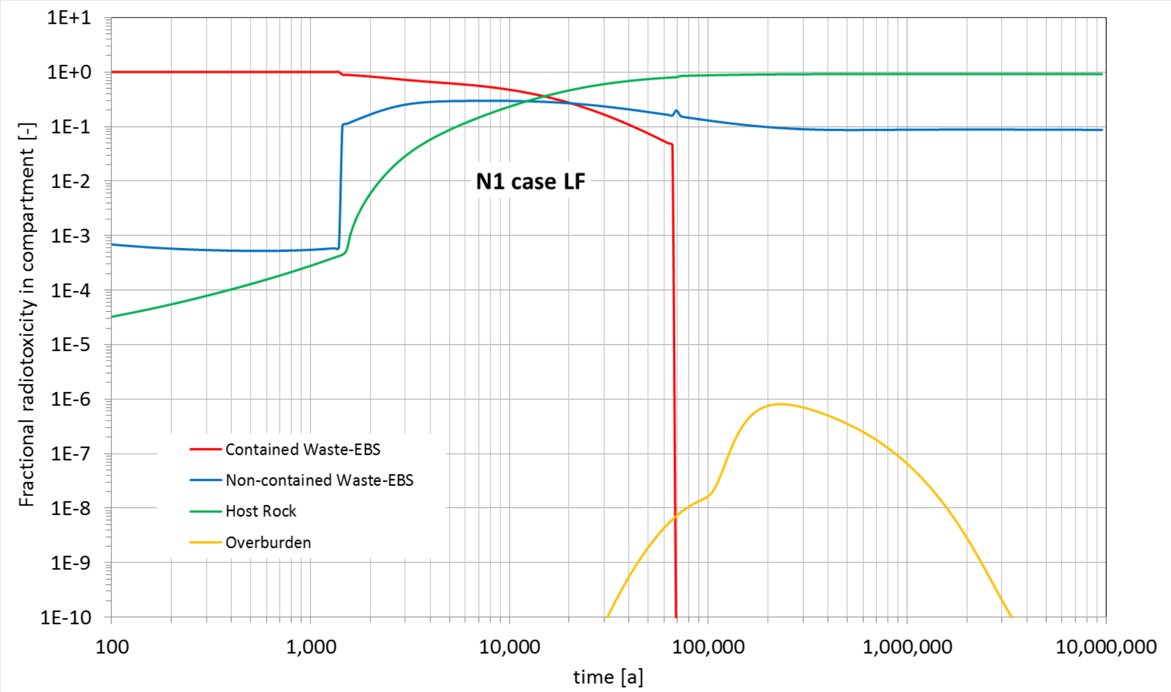

Figure 3-18 Fractional radiotoxicity of the different compartments of the repository system. Calculation case N1-LF. PA model version 9.3.

Observations:

- Before the failure of the Konrad containers (1500 a), almost all radiotoxicity is safely isolated in containers ("Contained Waste-EBS")
- After the failure of the Konrad containers (1500 a) a significant fraction of the total remains isolated in supercontainers declining in time due to decay
- After the failure of the supercontainers (70'000 a), still a significant fraction (> ca. 10%) of the total radiotoxicity remains - although uncontained - in the *Waste-EBS* compartment
- After the failure of the supercontainers (70'000 a), the host rock contains the largest radiotoxicity fraction (80%, increasing to about 90% on the long term)
- The radiotoxicity fraction in the overburden remains at least 6 orders of magnitude below fraction in the host rock

3.4. Early container failure & low DOC (EFLD)

This section presents the results of the *Early container failure* and *low DOC content* subcase of the *Central Assessment Case* of the *Normal evolution scenario* (N1-EFLD). The concentration of dissolved organic carbon (DOC) has no visible effect on the dose rate on considered the time scale therefore the results very similar to the N1-EF case, Section 3.2.

3.4.1. Effective dose rate (S1)

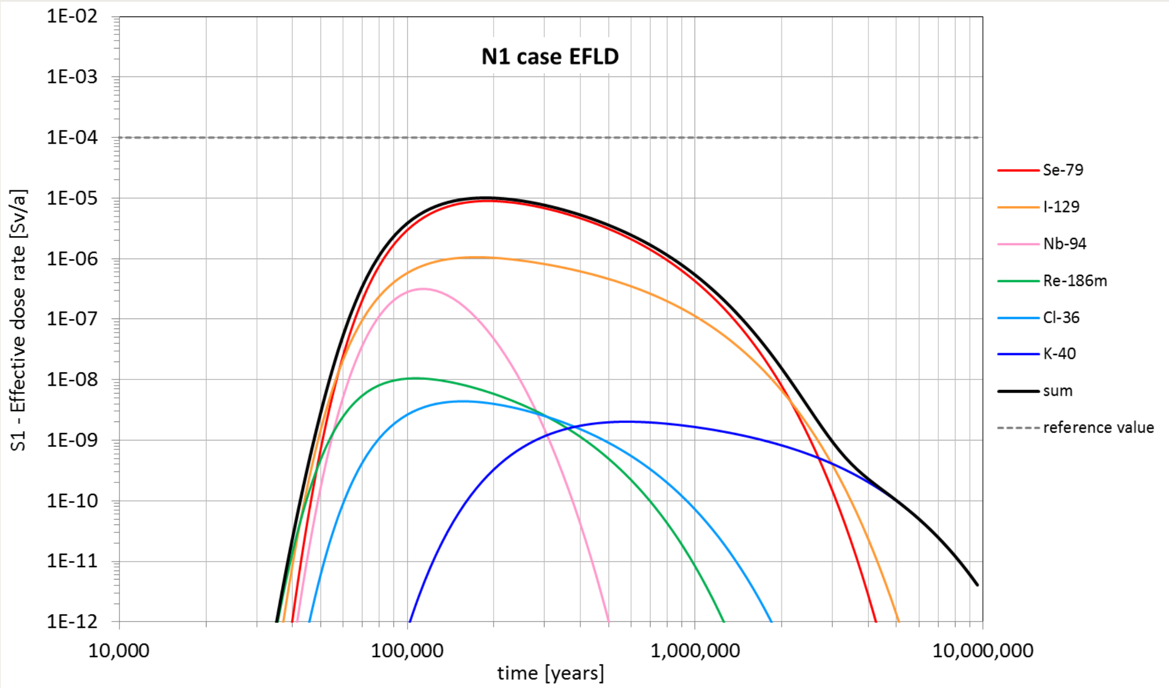

Figure 3-19 Effective dose rate (S1). Calculation case N1-EFLD. PA model version 9.3.

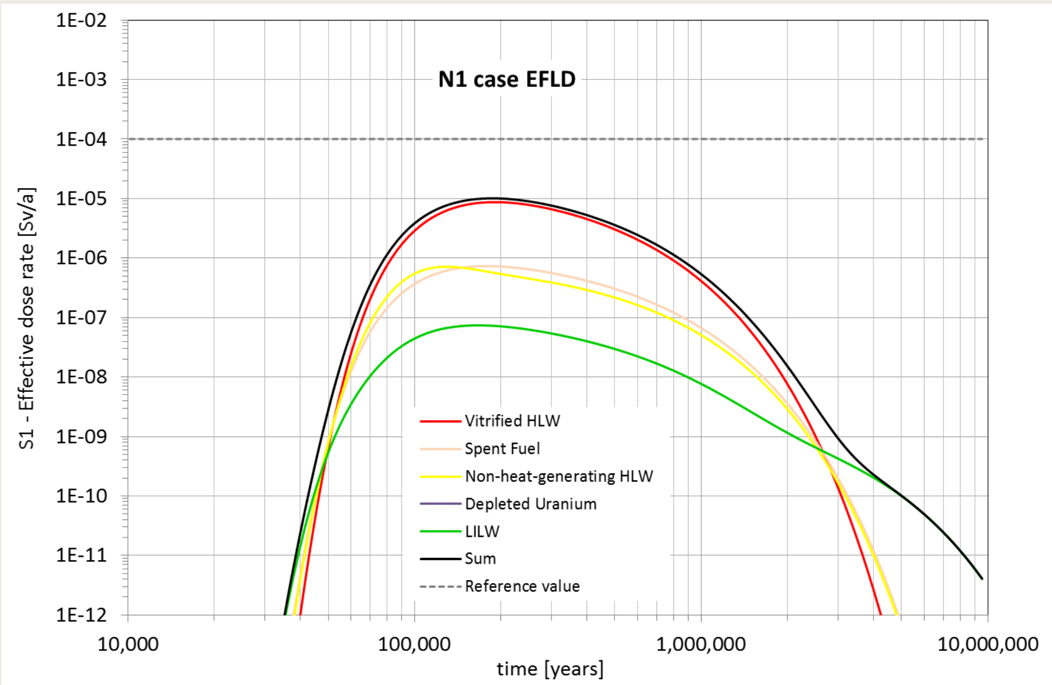

Figure 3-20 Contribution of the various disposal sections to the effective dose rate (S1). Calculation case N1-EFLD. PA model version 9.3.

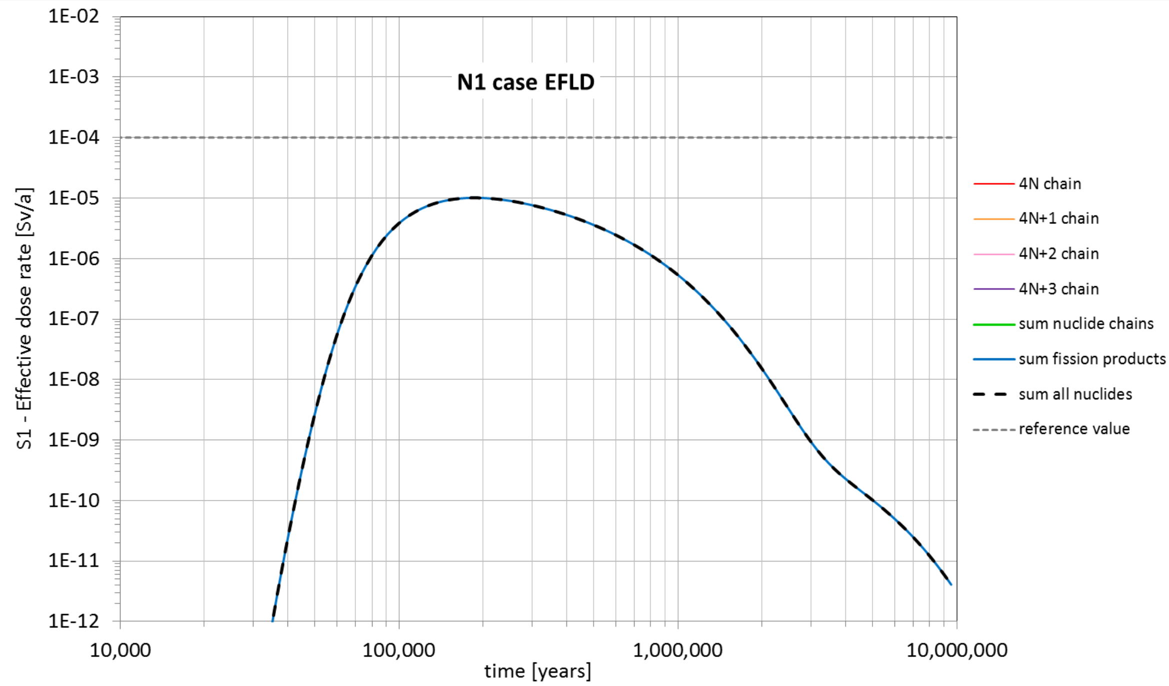

Figure 3-21 Contribution of the natural nuclide decay chains to the effective dose rate (S1). Calculation case N1-EFLD. PA model version 9.3.

Table 3-7 Maximum values Effective dose rate (S1). Calculation case N1-EFLD. PA model version 9.3.

Nuclide	***Time [a]***	***Dose Rate [Sv/a]***	***Predominant origin***
Se-79	1.91E+05	8.98E-06	Vitrified HLW
I-129	1.74E+05	1.06E-06	Spent Fuel / Non-heat-generating HLW
Nb-94	1.15E+05	3.17E-07	Non-heat-generating HLW
Re-186m	1.05E+05	1.06E-08	LILW
Cl-36	1.58E+05	4.40E-09	LILW
K-40	5.75E+05	2.03E-09	LILW
Maximum	**1.91E+05**	**1.01E-05**	

Observations: see Section 3.2.1, *Early container failure* (EF) subcase

3.4.2. Radiotoxicity concentration in biosphere water (S2)

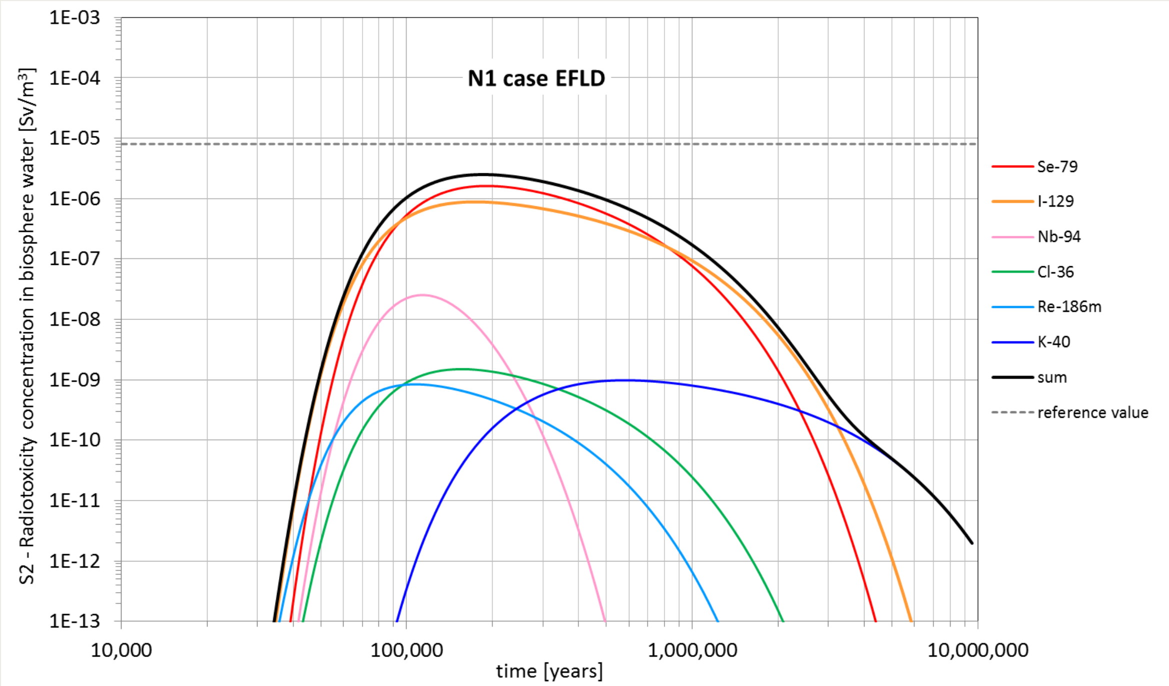

Figure 3-22 Radiotoxicity concentration in biosphere water (S2). Calculation case N1-EFLD. PA model version 9.3

Table 3-8 Maximum values Radiotoxicity concentration in biosphere water (S2). Calculation case N1-EFLD. PA model version 9.3.

Nuclide	***Time [a]***	***Radiotoxicity concentration [Sv/m³]***
Se-79	1.91E+05	1.62E-06
I-129	1.74E+05	8.82E-07
Nb-94	1.15E+05	2.53E-08
Cl-36	1.58E+05	1.50E-09
K-40	5.75E+05	9.82E-10
Re-186m	1.05E+05	8.41E-10
Maximum	**1.82E+05**	**2.50E-06**

Observations: see Section 3.2.2, *Early container failure* (EF) subcase

3.4.3. Performance of the integrated repository system (BI5)

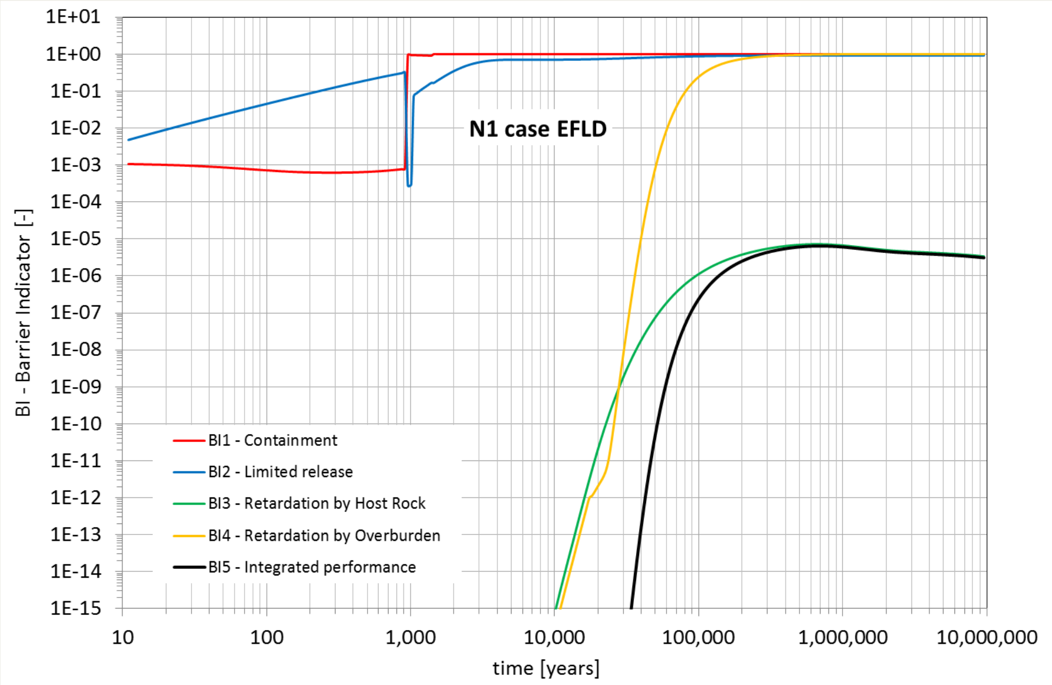

Figure 3-23 Performance of the integrated repository system (BI5). Calculation case N1-EFLD. PA model version 9.3.

Observations: see Section 3.1.3, *Early container failure* (EF) subcase

3.4.4. Fractional radiotoxicity in compartments (P4e)

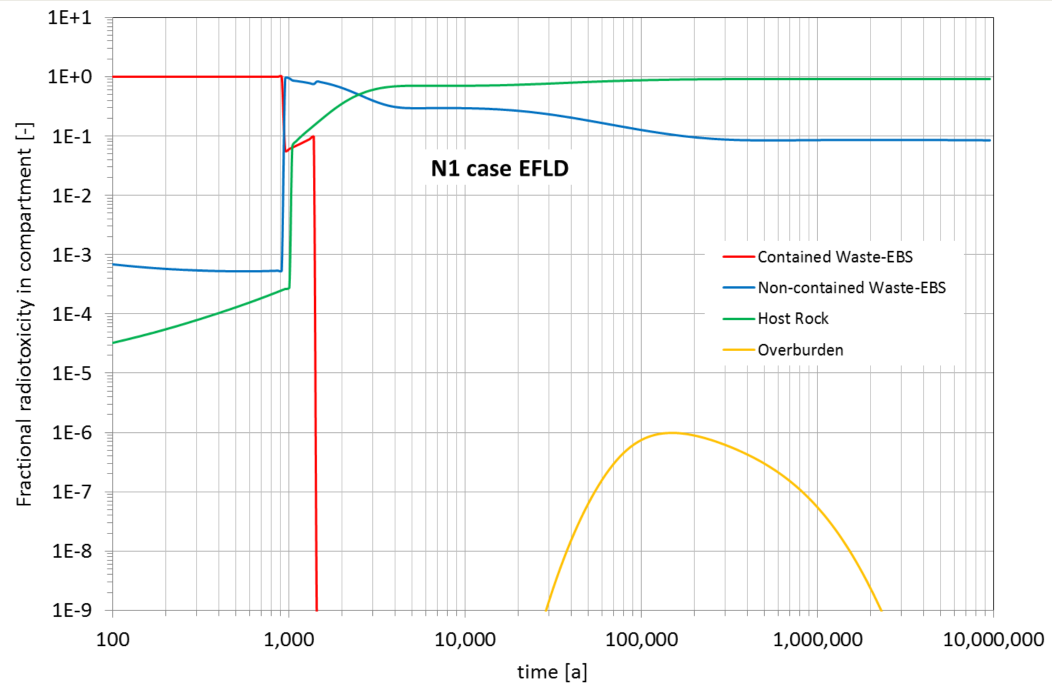

Figure 3-24 Fractional radiotoxicity of the different compartments of the repository system. Calculation case N1-EFLD. PA model version 9.3.

Observations: see Section 3.2.4, *Early container failure* (EF) subcase

3.5.Late container failure & low DOC (LFLD)

This section presents the results of the *Late container failure* and *low DOC content* subcase of the *Central Assessment Case* of the *Normal evolution scenario* (N1-LFLD). The concentration DOC has no visible effect on the dose rate on considered the time scale therefore the results are very similar to the N1-LF case, Section 3.3.

3.5.1. Effective dose rate (S1)

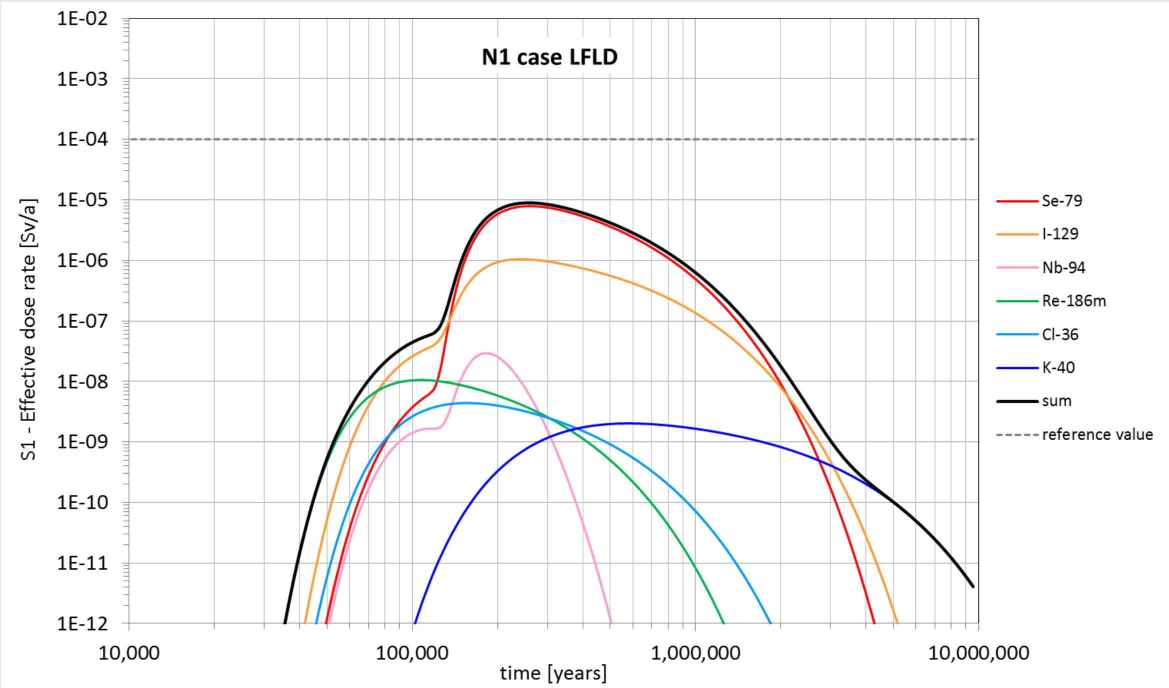

Figure 3-25 Effective dose rate (S1). Calculation case N1-LFLD. PA model version 9.3.

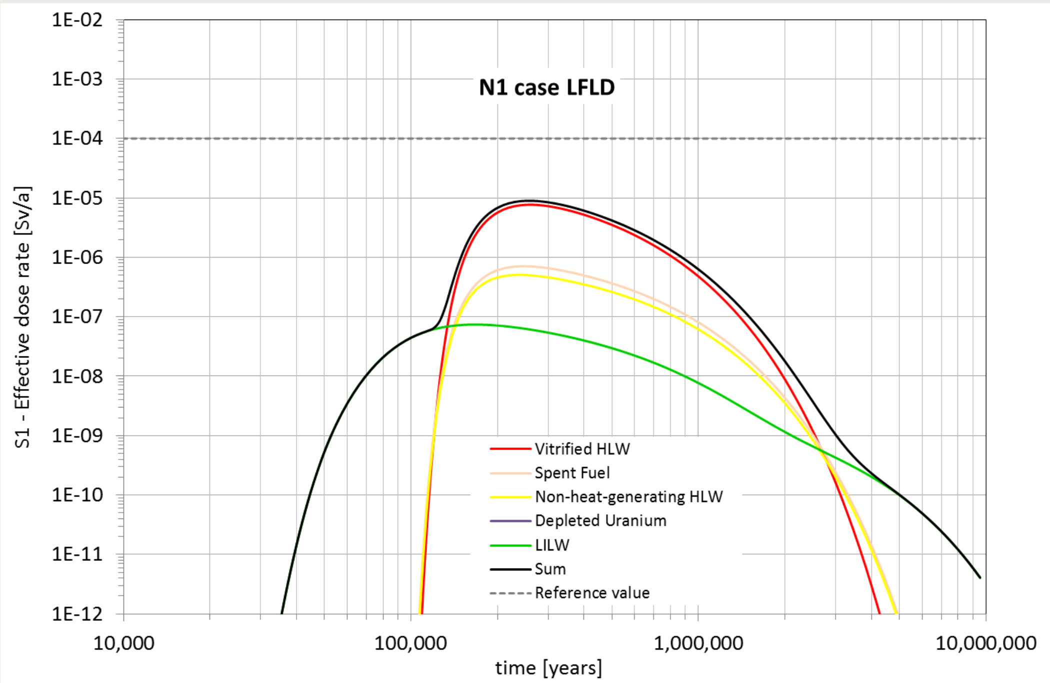

Figure 3-26 Contribution of the various disposal sections to the effective dose rate (S1). Calculation case N1-LFLD. PA model version 9.3.

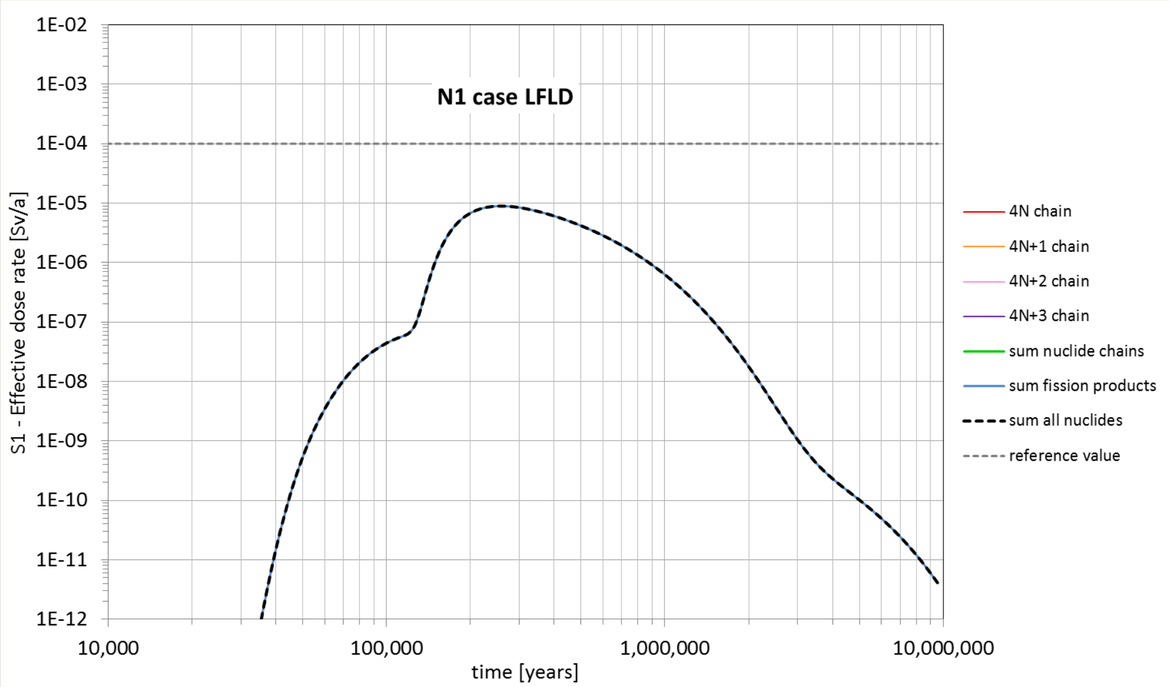

Figure 3-27 Contribution of the natural nuclide decay chains to the effective dose rate (S1). Calculation case N1-LFLD. PA model version 9.3.

Table 3-9 Maximum values Effective dose rate (S1). Calculation case N1-LFLD. PA model version 9.3.

Nuclide	*Time [a]*	*Dose Rate [Sv/a]*	*Predominant origin*
Se-79	2.63E+05	7.91E-06	Vitrified HLW
I-129	2.40E+05	1.05E-06	Spent Fuel / Non-heat-generating HLW
Nb-94	1.82E+05	2.94E-08	Non-heat-generating HLW
Re-186m	1.05E+05	1.06E-08	LILW
Cl-36	1.58E+05	4.40E-09	LILW
K-40	5.75E+05	2.03E-09	LILW
Maximum	**2.63E+05**	**8.95E-06**	

Observations: see Section 3.3.1, *Late container failure* (LF) subcase

3.5.2. Radiotoxicity concentration in biosphere water (S2)

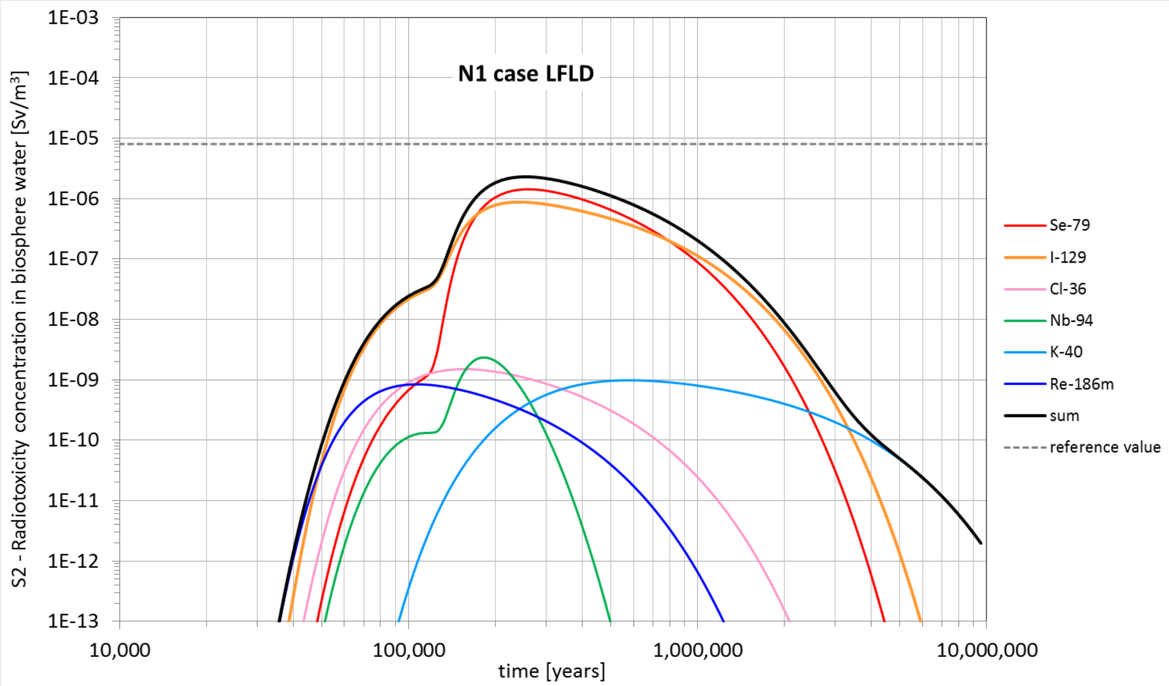

Figure 3-28 Radiotoxicity concentration in biosphere water (S2). Calculation case N1-LFLD. PA model version 9.3.

Table 3-10 Maximum values Radiotoxicity concentration in biosphere water (S2). Calculation case N1-LFLD. PA model version 9.3.

Nuclide	***Time [a]***	***Radiotoxicity concentration [Sv/m³]***
Se-79	2.63E+05	1.42E-06
I-129	2.40E+05	8.75E-07
Nb-94	1.82E+05	2.34E-09
Cl-36	1.58E+05	1.50E-09
K-40	5.75E+05	9.82E-10
Re-186m	1.05E+05	8.41E-10
Sum	**2.51E+05**	**2.29E-06**

Observations: see Section 3.3.2, *Late container failure* (LF) subcase

3.5.3. Performance of the integrated repository system (BI5)

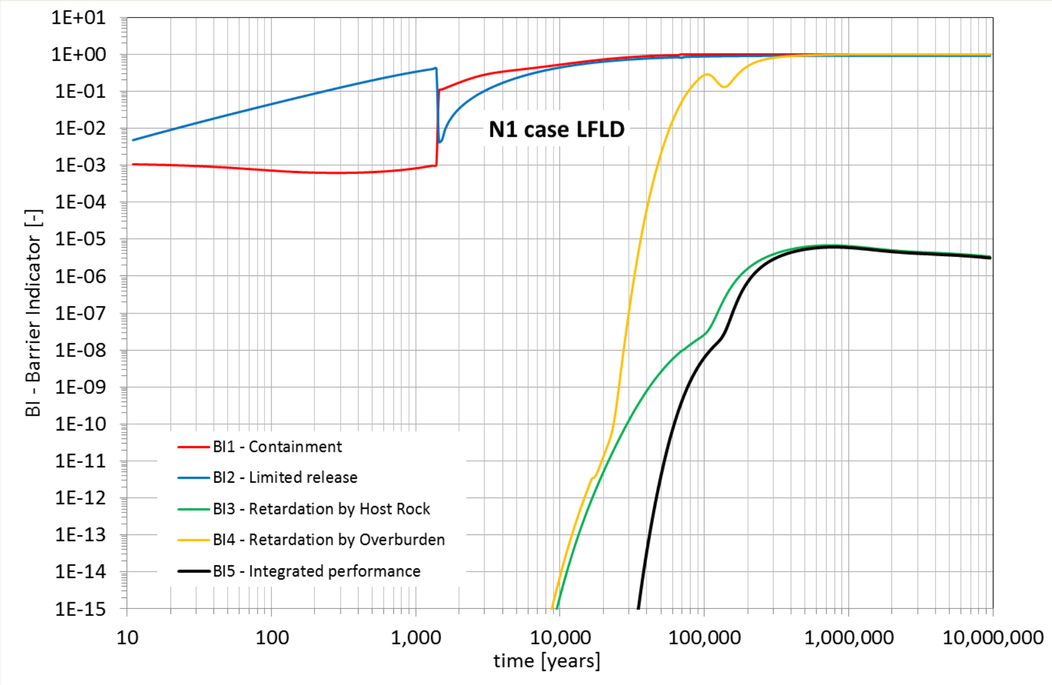

Figure 3-29 Performance of the integrated repository system (BI5). Calculation case N1-LFLD. PA model version 9.3.

Observations: see Section 3.3.3, *Late container failure* (LF) subcase

3.5.4. Fractional radiotoxicity in compartments (P4e)

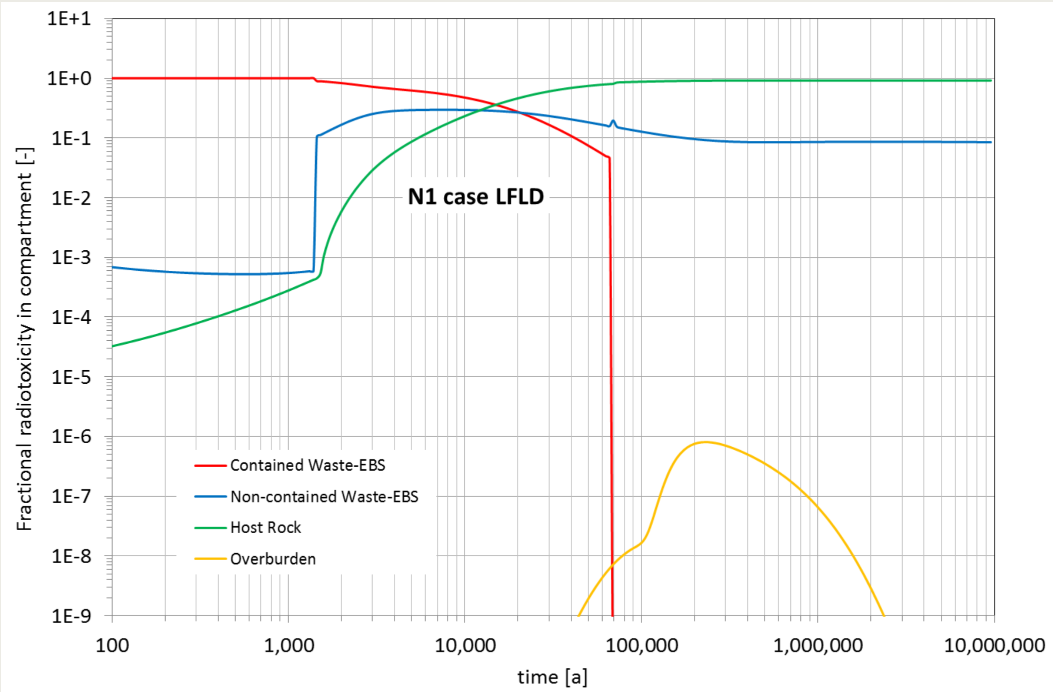

Figure 3-30 Fractional radiotoxicity of the different compartments of the repository system. Calculation case N1-LFLD. PA model version 9.3.

Observations: see Section 3.3.4, *Late container failure* (LF) subcase

4. Conclusions and discussion issues

This report contains the description and the results of safety assessment calculations carried out in the context of OPERA Task 7.3.3: Safety assessment calculations. The calculations presented in this report are performed by NRG and are carried out for the *Central Assessment Case* (N1) of the *Normal Evolution Scenario* (NES) and default parameters values (DV) as well as four additional cases identified as part of the Central Assessment case N1 (see Table 2-2). The results of these simulations will serve as input for the OPERA Safety Case report.

All calculated cases reveal a maximum for the effective dose rate at 190’000 - 260’000 years after disposal, due to the contribution of the mobile long-lived radionuclides ^{79}Se and ^{129}I, with a peak value one order of magnitude below the reference value of 0.1 mSv/a.

An overall overview of the results of the PA calculations of the Central Assessment Case’s base case and the four parameter variations analysed are summarised in the figure below.

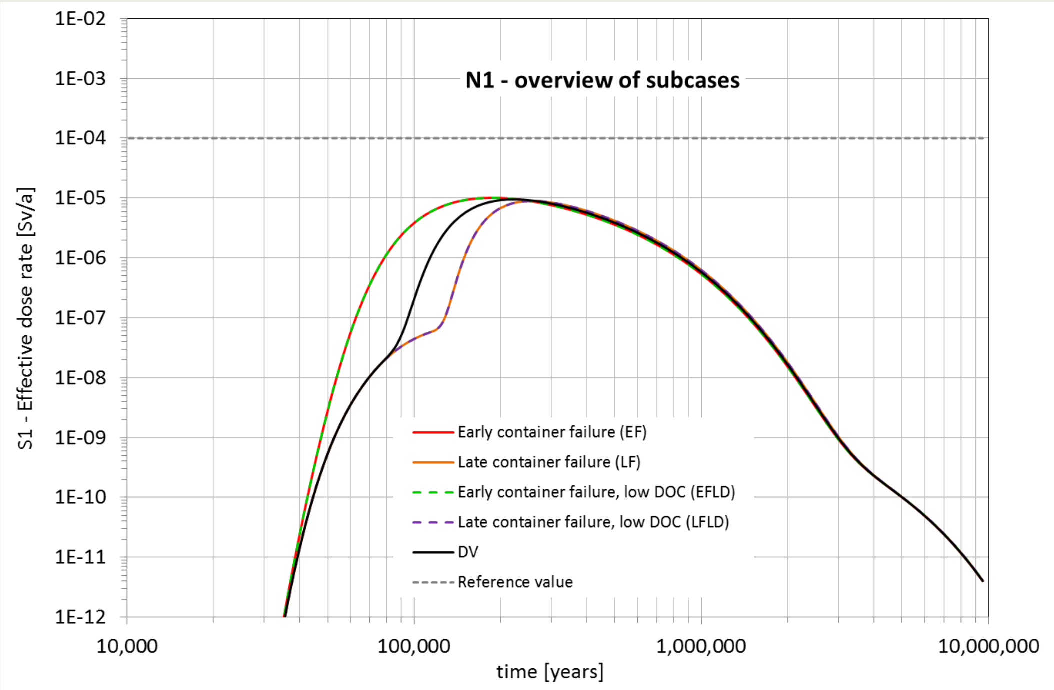

Figure 4-1 Effective dose rate (S1) - Calculation cases DV, EF, LF, EFLD, and LFLD

The calculation cases EF, LF, EFLD, and LFLD (see Figure 4-1) do not relevantly differ from the *Base Case* (DV) of C*entral Assessment Case*:

- the early failure cases having a 6% higher maximum dose rate, and
- the late failure cases a 6% lower maximum dose rate compared to the DV case;
- the concentration DOC has no visible effect on the dose rate on the considered time scale.

The main difference noticeable between the five cases calculated in Figure 4-1 is that

- in case of an early failure, the (limited) contribution of the LILW section to the overall dose rate is not visible, and
- in case of the late failure, the contribution of the LILW to the dose rate is more pronounced.

Furthermore, within the assessment period of 10 million years, the contribution of the four natural nuclide chains to the effective dose rate is negligible. An additional calculation did show that the onset of the breakthrough contributed by the natural nuclide decay chains (mainly arising from the DU and LILW sections) occurs at about 20 million years, and is estimated to dominate the overall risk (either in dose rate or in radiotoxicity concentrations) after 40 million years.

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